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PHYSICS.—*Gravitation an enigma.*[1]

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I am deeply appreciative of the opportunity to deliver this year's Joseph Henry lecture. As a Princetonian I am particularly grateful, for although the Philosophical Society of Washington may claim Joseph Henry as its founder and first president, Princeton also has a claim. For it was much earlier as professor of natural philosophy at Princeton University that Henry made many of his important discoveries. He might have been the first and was certainly not the last scientist to sacrifice his opportunity for research in order to serve the United States Government as an administrator.

Is gravitation an enigma? I fear that many of my colleagues would say no! In fact, for the past 250 years there have been only two accepted theories of gravity, each of which has enjoyed wide spread approval, of course not at the same time. The approval of General Relativity is such that for the past 40 years most physicists have not felt a need for any new fundamental experiments on gravitation.

It is difficult to realize how venerable is the original Newtonian theory of gravitation. For example, in 1837 when Joseph Henry was experimenting on electromagnetic induction at Princeton, Newton's law of gravitation had already been stated 150 years previously. A very extensive literature on the dynamics of the solar system had been produced including the important works of Euler, Lagrange, and Laplace.

Prior to Newton's theory of gravitation there had been no theory in the modern sense of the word. An elaborate philosophical description due to Descartes attributed gravitation to complicated vortices in an ether filled space called a plenum, but this was hardly a theory.

It is interesting to note that Newton's law of gravitation was not immediately accepted. As late as 1730, 43 years after the publication of Newton's Principia, Voltaire wrote, "A Frenchman who arrives in London will find philosophy like everything else very much changed there. He had left the world a *plenum* and now he finds a *vacuum.*"[2] The opposition to Newton's theory was largely philosophical. The inverse square law of interaction seemed to imply "action at a distance." The idea that two bodies could exert a force on each other at a distance and in a vacuum was highly objectionable, particularly to the French school brought up on the Cartesian philosophy.

Newton himself never regarded his theory of gravitation as more than an ad hoc formalism which seemed to work. In fact he wrote that, to suppose "that one body may act upon another at a distance through a vacuum, without the mediation of anything else . . . is to me so great an absurdity that I believe that no man, who has in philosophical matters a competent faculty for thinking, can ever fall in to it."[3]

He conjectured that gravitation might be associated with a variation in density of the ether from one place to another, with a body being pushed from a region of high density to a region of low density.[4]

[1] The 27th Joseph Henry Lecture of the Philosophical Society of Washington, delivered before the Society on April 18, 1958.

[2] WHITTAKER, *History of the theories of the ether*, 1: 29. London, 1951.

[3] NEWTON, *Principia.*

[4] WHITTAKER, loc. cit.: 28.

GENERAL RELATIVITY

Compared with the long period of difficulty experienced by Newton with his theory of gravity, Einstein's difficulties were short lived. For it is characteristic of Einstein's genius that he was able to construct a theory of gravitation which seemed to work and was esthetically satisfying. He was able to account for a small discrepancy observed in the orbit of Mercury as computed from Newton's laws. Further, his theory predicted an anomalous deflection of light by gravity, and this was later observed.

In a certain limited sense, Einstein's theory of gravitation, or the General Theory of Relativity, represent a return to the Cartesian philosophy, for Einstein's theory is a field theory, that is, the gravitational force acting on a body is assumed to have its origin in the space surrounding the body and not to be an "action at a distance." On the other hand, it must also be said on the philosophical side that General Relativity is not considered to be an ether theory of gravity, for the field is thought to represent the geometrical properties of the vacuum and not the properties of a "plenum." In fact the demise of the ether in 1905 was due in large measure to Einstein's contributions to the idea of Special Relativity and Lorentz invarience.

Einstein's theory of gravitation stems primarily from a single simple assumption. It had long been known that the gravitational acceleration of a body is quite accurately independent of its composition. Thus all objects in a freely falling box fall with it, and an observer in this box would be unaware of the presence of the gravitational field. Conversely an elevator accelerated in gravity-free space would seem to a passenger to be in a gravitational field. This suggests that a uniform gravitational field is completely equivalent to a uniform acceleration. This assumption is known as the "Principle of Equivalence."

From this point of view the common gravitational acceleration experienced by any small body at a given point in space is to be regarded as a property of the geometry of the four dimensional space-time continuum. Stated another way, a body projected at a given space-time point in such a way as to pass through another space-time point has followed a unique curve in the four dimensional space-time continuum between the two points and this curve is assumed to be determined by the geometrical properties of space. Following Einstein, the obvious curves uniquely determined by the geometry of space-time are the geodesics, i.e., curves representing the "shortest" distance, more properly extremum, between the two points.

It is found that to represent gravitation the proper definition of distance between two space-time points in the space is such that the resulting space is Riemannian. That is, the infinitesimal distance (ds) between two neighboring space-time points is defined by

$$ds^2 = \sum_{ij} g_{ij}\, dx^i\, dx^j \qquad (1)$$

Here as usual, the indices i and j are summed over 1, 2, 3, and 4. dx^i are coordinate differentials of the four coordinates necessary to specify the space time point. The metric tensor, with elements g_{ij} which are functions of the coordinates, completely specifies the geometrical properties of both the coordinate system and the space. The trajectory of a particle between two space-time points is specified by the requirement that the distance along the trajectory between the two points be a minimum, i.e., by the variational principle.

$$\delta \int ds = 0 \qquad (2)$$

where the integral is a line integral along the path. It should be emphasized that the definition of distance encompassed in equation (1) is assumed to be not completely arbitrary but to be the time or space interval which would be measured by actual material clocks or rods.

As stated above, in Einstein's gravitational theory there is no specific gravitational field quantity. The gravitational field is given wholly by the metric tensor g_{ij} which also specifies the various curvatures of space. The metric tensor is determined by a field equation in the form

$$R_{ik} - \tfrac{1}{2}\, g_{ik} R = \frac{8\pi G}{c^4}\, T_{ik} \qquad (3)$$

Here R_{ik} is a curvature tensor of the space. It is a function of the metric tensor and its first and 2nd derivatives. R is the curvature scalar.

$$R = \sum_{ij} g^{ij} R_{ij} \tag{4}$$

G is the gravitational constant, c the velocity of light and T_{ik} the energy-momentum tensor of matter with the matter energy density as the 4-4 component. The field equation (3) results from a variational principle

$$0 = \delta \int (L + R)\sqrt{-g}\, d^4x \tag{5}$$

where L is the Lagrangian density of the matter and $\sqrt{-g}\, d^4x$ is an element of volume in space-time. It should be stated that the equations of motion of matter are contained in the field equation (3) and that (2) is actually superfluous.

Equation (3) has been solved for the case of a spherically symmetrical mass distribution (Schwarzschild solution). The resulting metric tensor when inserted into equation (2) gives an equation of motion for the planet mercury about the sun which is in satisfactory agreement with the observations and accounts in a satisfactory way for the anomalous rotation of the perihelion of the orbit. It also predicts a deflection of very rapidly moving particles (e.g., photons) by the sun by an amount just twice what would have been expected from Newtonian mechanics. The gravitational red shift is also predicted. The first two effects seem to be in satisfactory agreement with observations and the third is qualitatively satisfactory.

We have here presented only enough of the frame work of general relativity to form a basis for discussion, and we now return to the question previously raised. Is gravitation an enigma?

GRAVITATION AS GEOMETRY

As a first point we notice an enigmatic dichotomy. Gravitation is described in a completely different way from other interactions. Gravitation is ascribed to the geometrical properties of empty space, but all other interactions are traced to local interactions between particles.

This is a peculiar situation with an interesting history which requires a bit of elaboration. We have seen how the difficulties encountered by Newton toward the end of the seventeenth century in obtaining acceptance of his law of gravitation were due to the conflict between the concept of "action at a distance" and the concept of local action of an ether on matter.

Interestingly enough, after the success of Newtonian mechanics in dealing with planetary motion became known, the pendulum had swung the other way. Action at a distance became the accepted concept, and the ether filled plenum was not required again until the beginning of the nineteenth century when Young's important experiments demanded a light wave for their explanation. To the physicist of this period, a wave without a medium to propagate it was unthinkable.

The idea of force fields in the form of local interactions of a tenuous medium (the ether) on matter was fundamental all through the nineteenth century. In fact, after Maxwell's electromagnetic theory, it became clear that light and all electromagnetic phenomena could be described in terms of waves in such an ether.

With Einstein's famous paper on special relativity in 1905, the ether concept was again in disrepute and for all practical purposes has been dead for the last 50 years. Its demise came about in a strange way. A number of electromagnetic experiments toward the end of the nineteenth century had been unsuccessful in measuring the velocity of the earth relative to the ether. It was shown by Lorentz and others that a contraction of matter in the direction of motion and a slowing down of the rate of clocks in motion, both by a factor

$$[1 - (v/c)^2]^{1/2} \tag{6}$$

where v is the velocity of the earth relative to the ether, would explain these results. Also it was later shown by Lorentz that these contractions would in fact result from his ether theory of the electron with a certain reasonable assumption as to the electron's structure. He furthermore showed that the mass of an electron in motion should increase by a factor of the reciprocal of (6).

In 1905 Einstein suggested that since it appeared to be experimentally impossible to measure a velocity relative to the ether, all inertial frames were equivalent and an inertial frame with the ether at rest was physically meaningless. Once again serious doubt was expressed concerning the existence of an ether. He argued that if the concept of velocity relative to an ether is physically meaningless, the ether must not exist, otherwise this motion would be physically meaningful. We shall return later to this question.

By 1916 the vacuum had become complicated. The curvature of space represented the gravitational field. The vacuum also carried the electromagnetic fields. One suspects that with empty space having so many properties, all that had been accomplished in destroying the ether was a semantic trick. The ether had been renamed the vacuum. This was a useful trick, however, as the mechanical connotation of the old name had been left behind.

After the discovery of the photon and the development of quantum mechanics in 1927, it was realized that what was formerly regarded as an abstract electromagnetic field in the vacuum could be visualized as a swarm of particles, the photons, being continuously created and destroyed. The electromagnetic forces could be traced to purely local interactions of the photons with charged particles. Thus what had been thought to be a vacuum was not a vacuum but contained photons. Furthermore, it was then realized that there were other forces (e.g. nuclear) and these also could be attributed to purely local interactions between particles. Only gravitation remained as a field property of empty space.

In recent years space has been getting even more complex, with a charged particle being surrounded by a halo of both photons and electron-positron pairs in virtual states. These particles do not materialize as proper well behaved specimens but have only a transient existence, being continuously replaced by new ones.

We thus see that all ordinary forces (e.g., electromagnetic and nuclear) are, from a physical point of view, believed to be due to purely local interactions of particles with each other. For example, the strong attraction between nucleons in the nucleus is believed due to collisions with virtual mesons (pions) which are being continually created and annihilated. Only gravitation and inertia are singled out as forces associated with empty space. This is an anomaly to which we shall return.

GRAVITATION A WEAK INTERACTION

The second way in which gravitation is anomalous is in its strength. It is the weakest of all known interactions.

It might seem strange to call the force of 2×10^{18} tons, required to keep the earth in its orbit, a weak force. However, stated on a per particle basis, and compared with other forces, it is extremely weak. For example, in the hydrogen atom the gravitational force between the electron and the proton is only 5×10^{-40} that of the electrostatic interaction.

The fact that the strength of the gravitational interaction is so different from other interactions might tend to strengthen the belief that it is completely different from other forces.

There are some reasons for believing that this is true. For over 35 years Einstein and many others attempted to extend the geometrical notions of General Relativity to obtain a theory of the structure of particles, and hence of other interactions, but without notable success. These attempts were called unified field theories. It is said that one well-known physicist, in referring to the unified field theories, commented, "Let no man join together what God hath put asunder."

On the other hand, there are empirical reasons for believing that the strength of the gravitational interaction is related to both the scale of the universe and the strength of the strong atomic interactions. By a strong interaction we shall mean an electromagnetic or nuclear interaction.

The empirical relations in question were first discovered by A. S. Eddington and are known as the Eddington numbers.[5] As the first of these dimensionless numbers we could take the ratio of the electrical to gravitational force between an electron and a proton. As was stated previously this is

[5] EDDINGTON, *The philosophy of physical science.* Cambridge, 1939.

$$\frac{e^2}{Gm_e m_p} = 2 \times 10^{39} \qquad (7)$$

In similar fashion the age of the universe ($T = 12 \times 10^9$ years) expressed in units of atomic time is

$$\frac{Tm_e c^3}{e^2} = 4 \times 10^{40} \qquad (8)$$

Another significant number is the square root of the number of heavy particles in the visible part of the universe. With the assumption of an average density of matter in space of $\rho = 10^{-30}$ gms cm^{-3} this is roughly

$$\left[\frac{\frac{4\pi}{3} R^3 \rho}{m_p}\right]^{1/2} = 1.7 \times 10^{39} \qquad (9)$$

Here $R = Tc$ is the "Hubble radius" of the universe. The approximate equality of these three numbers would seem to imply some sort of a connection between gravitational and atomic quantities.

It should be noted that the first number represents a connection between quantities usually called physical or atomic constants whereas the other two involve astrophysical or cosmological quantities expressed in atomic units.

An interesting derived quantity is obtained by squaring (9) and dividing by (7) and (8). This quantity which can be called the ratio of gravitational energy to matter energy in the universe is

$$\frac{\frac{4\pi}{3} R^2 \rho G}{c^2} = 0.036 \qquad (10)$$

It should be emphasized that these numbers are inaccurate. In particular the accuracy with which the density of matter in the universe is known is very poor.

What interpretation can be made of the Eddington numbers? That these relations should be accidental seems unlikely, but what is their significance?

DIRAC'S COSMOLOGY

A number of years ago P. A. M. Dirac[6] made an interesting suggestion regarding the Eddington numbers. He noted that one of the numbers (8) is proportional to the age of the universe. With the assumption that the rough equality of (7), (8), and (9) is independent of time, he concluded that, compared with electrical interactions, the gravitational interactions are steadily getting weaker. More exactly, the gravitational constant G varies inversely as the age of the universe. He also concluded from the equality of (7) and (9) that the number of particles in the visible part of the universe varies as the square of the age of the universe. This later conclusion does not necessarily imply the creation of new particles as the boundary of the visible part of the universe may move outward to encompass more particles in the interior.

Dirac's hypothesis is very interesting as it suggests that the gravitational interaction between two particles is not a purely local phenomenon but depends upon distant matter. As the amount of matter in the visible universe becomes greater, the gravitational interaction becomes weaker.

If Dirac's hypothesis is correct, there are many important implications for geologists and astrophysicists. Some of these have been previously discussed.[7] We here merely summarize very briefly some of the important effects.

(a) The radiation rate of the sun varies as G^7. The sun must then have been hotter in the past.

(b) With a constant albedo (i.e., visual surface reflection coefficient) the surface temperature of the earth would vary with the age of the universe as the -2.25 power of the age.

(c) The albedo of the earth would actually change with the water vapor content of the atmosphere. This would tend to stabilize the earth's temperature for the past few billion years.

(d) For an age of the universe of 12×10^9 years, and an age of the solar system of 4×10^9 years, the increased radiation rate of the sun in the past would have required a conversion of roughly 20% of the hydrogen into helium. The rapid burning in the past would have been obtained through the use

[6] DIRAC, Proc. Roy. Soc. **A165:** 199. 1938.

[7] For a summary see R. H. DICKE, Rev. Mod. Phys. **29:** 355. 1957.

of the carbon cycle rather than the *p-p* reaction presently the dominant one. This would lead to a convective core in the sun serving to mix the helium throughout the core. It is possible that a thorough mixing of helium throughout the whole sun might have occurred at some time in the past.

(e) In addition to the effects associated with an original high surface temperature, there are many other important geological effects. For example, the earth gradually expands with time. This could be an explanation for the apparent relation between the coast lines of the land masses bordering the Atlantic Ocean and the mid-Atlantic ridge.

(f) The gradual decrease of gravitation would lead to a continuous slowing of the rate of revolution of the planets and the moon compared with the rotation rate of the earth. This seems to be observed although there are several other possible explanations, including an increased rotation rate of the earth produced by atmospheric tides, melting ice masses etc.

(g) The gradual reduction of pressure inside the earth leads to a continual slow convection of the earth's mantle carrying heat to the surface. The computed rate of heat transfer is about 5×10^{-7} cal/cm^2 sec and this is compatible with the observed rate of heat flow after making allowance for heat from radio-activity. There appears to be some geological evidence that such a convection does actually exist in the earth's mantle.

By comparing these conclusions, and many others, with the observed history of the solar system, it may be possible to exclude Dirac's hypothesis. It would be truly remarkable if geology and astronomy could answer such a fundamental physical question about the gravitational interaction.

Although there are a number of reasons for accepting Dirac's hypothesis, there is also some evidence to the contrary. For example there is evidence for glacial deposits over 1 billion years old. It is difficult to understand such deposits if the sun were substantially hotter at these times.

It is interesting to note therefore that Dirac's argument has a logical loop hole. To infer the time dependence of the gravitational interaction requires more than a simple observation that the reciprocal of the gravitational constant and the age of the universe, when expressed dimensionalessly, are *now* nearly equal. It is also necessary to assume that *now* is a random time. But is it?

The present epoch is conditioned by the fact that the biological conditions for the existence of man must be satisfied. This requires the existence of a planetary system and a hot star. If we assume an evolutionary cosmology starting with the formation of hydrogen 12 billion years ago, there is an upper limit for the epoch of man which is imposed by the following two conditions. First, hydrogen is being continually converted to helium and heavier elements. Perhaps 20% has already been "burned." The formation of new stars is thus limited to perhaps the first 10^{11} years. Second, there is an upper limit on the radiating life of a star.

If the star is massive (10 times the sun's mass) it lives riotously, burning its hydrogen like a wastrel. For a light star ($\frac{1}{10}$ the sun's mass) hydrogen is burned slowly and the star is capable of living much longer than the sun, 100 times as long. However, if the star is much smaller than this, its central temperature never rises high enough to cause nuclear reactions to take place. Such a light star radiates until its gravitational energy is gone and then it cools off. It is seen therefore that the longest life of a star is very roughly 10^{12} years and this puts an upper limit on the epoch of man.

There is also a lower limit on the epoch of man. With the assumption that initially only hydrogen exists, it is necessary to produce other elements in the stellar caldrons and distribute them about the universe before a planetary system of our type can be formed. It is a bit difficult to estimate this time but it would seem that 1 billion years would be a reasonable lower bound on the epoch of man.

It is thus seen that the epoch of man is not random but is fairly sharply delineated. Thus it is possible that the strength of the gravitational interaction is not determined by the immense scale of the universe, but that conversely the scale of the universe and the present epoch is determined by the relative strengths of the strong and weak interactions.

From this point of view the Eddington

number (7) is fundamental, (8) is determined by biological considerations and only (9) requires an explanation. Presumably the significance of (9) is lost in the mystery of the original creation of hydrogen, for this number is determined by the density of matter. We shall return later to a possible explanation of this number.

One unsatisfactory feature of the above explanation of the numerical relations (7), (8), and (9) is that it does not give a satisfactory account of the enormous size of these numbers. It would be hoped that eventually an atomic constant such as the dimensionless number (7) would result from some theory of particles. But how could a number such as 10^{40} be expected to appear in a theory for which all other dimensionless numbers are small?

Here, Dirac's cosmology is more satisfactory. The large size of the Eddington numbers is considered to be purely accidental since the epoch *now* is taken to be random.

It is possible to construct cosmologies which lie somewhere between these two extremes. It could be assumed that the epoch *now* is not random but determined by the strengths of the weak interactions in the manner previously described. On the other hand the strength of the weak interactions might be determined by the structure of the universe. For example the number of particles in the universe might be large as a result of some chain reaction and this large number might determine the strength's of the weak interactions in some way not presently understood.

It is evident that all these cosmological models are highly speculative. However, one feature they have in common is not easily avoided. They all imply some sort of interrelation between the strong and gravitational interactions.

ABSOLUTE SPACE, MACH'S PRINCIPLE AND GRAVITATION

It will be recalled that it was largely Einstein's influence which led to the rejection of an absolute space as an allowable physical concept. However, Einstein's theory of gravitation does make use of some of the concepts of an absolute space. For example inertial coordinate systems are assumed to have a well defined meaning even in the absence of gravitating matter.

Also it appears to be a basic assumption of Einstein's theory that such geometrical concepts as points, curvatures, and geodesics are meaningful for a vacuum. The conceptual difficulty of defining these concepts and of describing motion relative to such an empty physical space is ameliorated by imagining space filled with a set of massless test particles. By moving on geodesics of the space, these particles serve to make evident the underlying geometrical structure of space. This underlying geometrical structure is thus regarded as a property of an absolute space. While it is true that the geometry of space is affected by the presence of gravitating matter, General Relativity is usually thought to give meaningful results even in the absence of matter.

The conceptual difficulties with ascribing physical properties to a vacuum have been long apparent. That there should be preferred coordinate systems (the inertial systems) in empty space is difficult to comprehend. This is a very old problem, and still without a solution. Many years ago Mach[8] made an interesting suggestion which has come to be known as Mach's Principle. According to this principle it is not acceleration relative to empty space that produces an inertial force. This force is considered to be due to the acceleration relative to distant matter in the space. From the point of view of a strict relativist, the effect can also be said to be due to an acceleration of the distant matter relative to the stationary particle experiencing the inertial force.

The inertial force is not considered to be a new and different type of force but simply the gravitational interaction with distant matter. A particle at rest with respect to distant matter finds itself surrounded by a spherically symmetrical universe, and all gravitational forces cancel. If distant matter is accelerated, there is an unbalanced gravitational force acting on the particle in question and this force is called the inertial force.[9]

For example, the earth accelerating toward the sun can be considered at rest in a

[8] E. MACH, *The science of mechanics*, ed. 6. 1904.
[9] D. SCIAMA, M. N. **113**: 34. 1953.

particular coordinate system for which the total gravitational force on the earth is zero. This force is composed of the gravitational pull of the sun on the earth and the gravitational interaction of the remainder of the universe.[9]

From the point of view of Mach's Principle, the inertial mass of a particle is determined by distant matter. From the point of view of Einstein's theory the inertial mass is a purely local property of the particle.

Interestingly enough, the actual structure of the universe appears to be compatible with Mach's Principle, at least to the extent that the structure is known. This is easily seen by considering an old problem solved by Thirring.[10] Thirring used the weak field solution to Einstein's field equations to find the rotation of the inertial coordinate systems inside a massive rotating spherical shell. He found that the inertial coordinate axes rotated with an angular velocity ω relative to distant inertial axes where

$$\omega = \omega_0 \frac{8Gm}{3aC^2} \tag{11}$$

Here ω_0 is the angular velocity of the rotating shell, m is its mass and a its radius.

In similar manner, from the point of view of Mach the Coriollis force experienced in a rotating laboratory is due to the gravitational field produced by distant matter wheeling around in a set of concentric shells. In this case the rotation rate of the inertial coordinate system ω is equal to the rotation rate of the distant matter ω_0 and Eq. (11) becomes

$$1 = \frac{32\pi}{3} \frac{G}{c^2} \int_0^R [\rho] r \, dr \tag{12}$$

Here the distant matter is treated as a set of concentric shells out to the Hubble radius R. $[\rho]$ is an effective density of matter and is equal to the observed density only for $r \ll R$, for the weak field solution is valid only under this condition. It would be expected that equation (12) could be written approximately as

$$\frac{GM}{Rc^2} \sim 1 \tag{13}$$

[10] Phys. Zeit. **19:** 33. 1918; **22:** 29. 1921.

where M is the mass in the visible part of the Universe.

The relations, equations (12) and (13) appear to hold for the actual universe to within the accuracy of the observation. See equation (10).

It must be emphasized that General Relativity itself does not require a condition of the form of equation (12) but that such a condition is compatible with General Relativity. Hence, it is conceivable that some solutions of Einstein's field equations are compatible with Mach's Principle and that Mach's Principle determines which are physically meaningful solutions.

From this point of view it would be hoped that Mach's Principle should appear as a boundary condition upon solutions to Einstein's field equations, the allowed solutions being only ones which are compatible with Mach's Principle. Attempts of Komar and others to introduce such conditions into Einstein's theory have not yet been successful.

It is also possible that the absolute inertial properties of space are an essential part of Einstein's theory of gravitation and that the theory is incompatible with Mach's Principle. Indications exist that this is true; Einstein's theory may not be compatible with Mach's Principle. Consider, for example, the space inside a hollow spherical mass shell. According to the interior Schwarzschild solution of Einstein's equation, the space is flat and has inertial properties independent of either the mass or radius of the sphere or of the existence of other exterior concentric mass spheres. Thus according to Einstein's theory the presence of this matter has no locally observable effect on the interior.

However, consider again equation (11); it can be combined with equation (13) to give

$$\frac{\omega}{\omega_0} = \gamma \frac{m}{M} \frac{R}{a} \tag{13a}$$

with γ a number of the order of unity. This expresses the ideas of Mach very neatly. The ratio of the two precession rates is in the ratio of the masses and inversely in the ratio of the radii of the mass spheres. On the other hand, the ratio M/R, as seen locally, is easily changed. For example, the rotating

sphere could be surrounded by a large fixed spherical shell, in addition to distant galactic matter, effectively changing the integral in equation (12) and hence the effective ratio M/R. According to equation (13a) such a change would result in a change in the ratio ω/ω_0, a locally observable effect. From equation (11) this implies a change in the quantity

$$\frac{Gm}{ac^2}$$

This change is to be traced to a change in the inertial forces. On the other hand, with local units defined in terms of atomic units, m and a are unchanged by definition. Also c could not change or there would be large observable violations of the Principle of Equivalence.[11] The only possibility is a change in G as it is observed locally. With this interpretation, equation (12) gives the locally observed value of G^{-1} as an integral over all the observed matter assumed to be isotopically distributed. With this interpretation, however, the numerical constant of equation (12) must also be questioned as it is based on General Relativity which is now invalid under this interpretation.

It should be noted that from equation (12) the presence of near by matter affects the local gravitational constant by an appreciable amount. Although the sun is hardly distributed isotropically about the earth its presence should change G by an amount of the order of

$$\frac{\Delta G}{G} = -\tfrac{8}{3}\frac{GM}{rc^2} = -2 \times 10^{-7} \quad (14)$$

Another possible effect of distant matter on inertial mass would appear as a velocity dependence of the gravitational constant. The uniform motion of a laboratory relative to distant matter might result in a change in the gravitational constant observed in the laboratory. Any such change should be proportional to the square of the velocity relative to distant matter.

Mach's Principle provides a possible explanation for the Eddington number's, equations (7), (8), and (9). We note first that equation (10), after making allowance for the inaccuracies in the numbers, is equivalent to equation (12). Secondly, the gravitational constant and the size of (7) is conditioned by the size of the universe, through equation (12). The number (8) is determined by biological conditions in the manner previously described. The number (10) is determined by (7), (8), and (11). The enormous size of (7) is related to the large number of particles in the universe and the reason for this will not be understood until a mechanism for the creation of matter is found.

Dirac's hypothesis that G varies with the age of the universe is understandable from the point of view of Mach's Principle. In fact equation (12) implies that G is constant only if M/R is constant as the universe evolves. On the other hand, the structure of the universe may be such that the ratio M/R does not change with time. Thus with the assumption of this form of Mach's Principle G can be either varying or constant as a function of the time.

MACH'S PRINCIPLE AND THE ETHER

As we have seen, only gravitation and inertia are considered to be field properties of the vacuum. All other forces are assumed to be caused by local interactions between particles, real or virtual. To ascribe such physical properties to the vacuum has long been considered objectionable.

It has been seen from the strength of the gravitational interaction that there are reasons for believing that gravitation is not completely different from other interactions. This suggests that gravitation be treated like other forces. It might be imagined that a gravitating mass is surrounded by a swarm of virtual particles and that the gravitational interaction involves only local interactions with these particles. It would be expected that a quantization of the gravitational field might result in such a particle picture of gravitation.

This picture of gravitation has several advantages. The dichotomy between gravitation and ordinary forces has disappeared, gravitation is *not* a property of the vacuum, local interactions between particles can be treated in accordance with the general relativity principle, and an action at a distance

[11] R. H. DICKE, Rev. Mod. Phys. **29**: 363. 1957.

principle is not needed. The general relativity principle states that the only physically meaningful motions are a matter relative to other matter. Mach's Principle follows from the general relativity principle.

Inertia effects would be treated in the manner described previously as a gravitational interaction with matter at great distance. Thus the contribution to the density of the virtual particle field falls off as r^{-1} and distant matter is more important than near by matter in determining the inertial properties of space.

Such a picture of space provides the extra degree of freedom needed for a variable gravitational constant (G). Two regions of space, both free of gravitational fields, may have different densities of virtual particles and different gravitational constants.

It will be noted that the picture of gravitation which is being drawn is very similar to the ether theories long rejected. In this connection it is interesting to note that the old objection of Einstein and others to the ether concept no longer holds. An ether consisting of a swarm of virtual particles, all in motion, may present the same appearance to two observers moving relative to each other. If it be assumed that the velocity distribution of the virtual particles is Lorentz invarient, the swarm of virtual particles (the ether or plenum) would look the same to all uniformly moving observers.

There is one difficulty with such an assumption. Such a distribution implies particles with arbitrarily high momentum states. If such momenta are excluded, Lorentz invarience would not be exact. Anomalies would show up at very high energies. From this point of view Lorentz invarience is not the simple fundamental invarience that is presently believed. It does not have the fundamental significance of the general relativity principle.

MODELS AND FORMALISM

One can hardly drag the "ether", kicking and screaming, back into the laboratory for serious consideration without saying a bit about the role and significance of such a concept as the "ether" for modern physics. Since the time of Newton there have been two diametrically opposed techniques for inductive reasoning in physics. Each has contributed a great deal to the development of physics.

Newton was probably the first exponent of the formal approach. In the *Principia* Newton states: "I have not been able to discover the cause of those properties of gravity from phenomena and I frame no hypothesis!"

In the formal approach to the physical world, only the physical observables are regarded as of physical significance, and the role of theory is one of giving a purely formal description of the relations between observables. The great advantage of this technique is that a problem is simplified to its bare essentials. A complicated substratum, existing perhaps only in the human mind, is ignored.

Thermodynamics is a very good example of a formal theory. The observables are such quantities as temperature, density, heat, energy, etc. The complicated substratum of moving molecules is ignored in constructing the theory.

A good example of the model approach to inductive reasoning is furnished by the molecular model of a gas and the resulting kinetic theory and statistical mechanics. This model is very old and was used by D. Bernoulli in 1738 to formulate a primitive kinetic theory of gases. The model was ignored for 100 years thereafter until the middle of the nineteenth century when it was again used to explain a variety of things. It should be remembered that practically the whole of the presently accepted kinetic theory of gases and statistical mechanics was originally based on a model which was not at the time subject to a direct experimental check.

For the past 30 years formal theories have dominated physics, and this has been coupled with an insistence on an operational definition of the observable quantities. This is in marked contrast with the nineteenth century when the model approach was the dominant one. If the present atmosphere of a completely formal approach had been dominant during the nineteenth century, it is very doubtful that the kinetic theory of

gases would have appeared until it had been forced by direct experimental observation of the molecules.

What then is the significance of a model such as the "ether"? This has a simple answer. To the extent that the model is beyond observation, it is simply a figment of the imagination has has no place in physics. However, to the extent that the model represents phenomena which are observable or may be some day observable, and to the extent that the model suggests new experiments and new theoretical developments, it is useful. One can go too far in requiring a strict and immediate observable significance for all physical concepts employed. What is important is the realization that the end results should be subject to observation.

SUMMARY

We started with Descartes' gravity, a maelstrom in a plenum, and ended with the speculation that both gravitational and inertial forces may be due to a bath of particles in rapid motion interacting with matter. We considered the mysterious Eddington numbers, Dirac's hypothesis of a time varying gravitational constant, and the implication of Mach's Principle. The remarkable fact was considered that the history of the solar system seen through the eyes of astronomers and geologists may enable fundamental conclusions to be drawn regarding physical interactions in the past.

The chief conclusion that can be distilled from the above discussion is that it is a serious lack of observational data that keeps one from drawing a clear portrait of gravitation. Each tiny fragment of information appears as a star shining through a murky haze. Conclusions regarding the most fundamental of physical concepts are based on numbers which may be off by a factor of 100. In any case it appears clear that there is little reason for complacency regarding gravitation. It may well be the most fundamental and least understood of the interactions.

If we were to select the most intelligent, imaginative, energetic, and emotionally stable third of mankind, all races would be represented.—FRANZ BOAS.

PHYSIOLOGY.—*The physiology of aging—a research approach.* JOSEPH W. STILL, Washington, D.C. (Communicated by C. H. Page.)

(Received May 28, 1958)

In a previous paper entitled *Are organismal aging and aging death necessarily the result of death of vital cells in the organism? (a cybernetic theory of aging)* (1) it was shown that it is possible for a multicelled organism to die (be disorganized) even though all its vital cells might still be alive. Thus, a sharp distinction was drawn between cell life (and death) and multicelled organismal life (and death). From that fact it was inferred that unicellular aging (if it occurs) is an entirely different phenomenon from multicellular aging, which is the aging phenomenon most interesting to us as humans.

That article also presented a simplified model of the central control panel in the brain which regulates the organism as a whole through nervous-endocrine mechanisms.

In this paper an attempt will be made to relate those ideas of central control to the physiology of peripheral cells in order to make an operationally more complete theory of aging so as to suggest, as the result of this analysis, some further research steps which need to be taken.

In the paper mentioned above the overall change in physiological response with advancing age was illustrated by means of the accompanying ideograph (Fig. 1).

This graph indicates that while, with advancing age, the range of response to both acute and chronic stimuli may narrow somewhat, the most striking change is a slowing of the rate of response. The changes in acute nervous reaction times are so well known as to require no proof here. To present the chronic changes in more detail, the following ideograph [Adopted from Selyes' *Stress* (2)] which compares the General (endocrine) Adaptation Syndrome response of young and old animals to chronic stressing agent(s) has been prepared (Fig. 2).

In the older animal the phases of reaction and recovery are somewhat slower, just as in acute nervous responses. Hence, the resistance phase is later in developing. Also, the old animal is unable to withstand a chronic stress for as long as the young (adult) one, and so the exhaustion phase ending in death arrives earlier in the old than in the young animal. Possibly the resistance to many chronic stressors is actually stronger in the middle than in younger life, but measurements and data are not yet sufficient to allow us to discuss such fine points as this at present.

These chronic curves provide an over-all description of the changes in resistance of the whole organism to stressors at the young and old stages of life. If we are going to learn how to increase the resistance (i.e., change the G.A.S. curve) of the older individual toward the youthful curve we must learn what is going on at the cell level and eventually at the molecular level *in the cells of the control center*. I believe cybernetic principles can help us take this step.

Let us begin with a schematic "cell's-eye"[1] view of life (Fig. 3), which summarizes the principal events which may occur and the mechanisms which control them at the cellular level for all cells.

Each cell swims and lives in a little pool of interstitial fluid called ground substance. This is a remarkable solution which is in a constant state of physico-chemical change in many ways. It carries food, oxygen, and other materials to the cell from the blood capillary highways serving that cell. The ground substance also returns metabolic wastes from the cell to the capillaries. At the edges of the interstitial pools are the remarkable all-purpose capillary highways, which bring fresh food, oxygen, etc., from afar to replace those which the cell removes from its ground substance pool. These highways also remove waste products which the cell dumps into its pool and thus main-

[1] I hope the reader will excuse my talking in allegorical fashion as I describe the cell's life. I do so because it greatly simplifies the problem of description, and also avoids the need for excessively precise statements which would slow down the description and add nothing to the meaning.

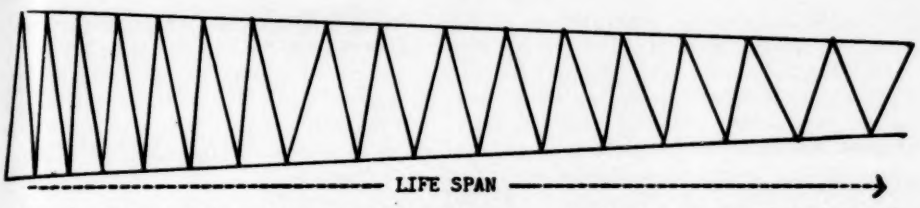


FIG. 1.—Characteristic age change, in homeostatic response to stressors, of physiological variables (such as temperature).

tains the pool's sanitary state. Life is pretty simple for the average cell, but there are "problems" and "worries" at the cell level, too. It is important that the fluid in the pool remain pretty stable in many different respects. It must be neither too hot nor too cold. It must have a pretty steady salt content. Its degree of acidity must be pretty steady. The pool must contain various amounts of the different food elements: sugars, fats, proteins, and vitamins, as well as the necessary work orders (enzymes, hormones, etc.) which its cell requires to keep it working in harmony with all the other cells of the organism. Finally, the fluid pool must be liquid (juicy) enough so these substances can easily pass to and from the cell as needed. If the pool fluid gets too gel-like—too thick—we can easily imagine the difficulties this would create.

One of the "worries" of a cell is due to the fact that there is a traffic control operator at the "corner" where its particular stretch of highway begins. Through some mysterious mechanism not understood by the cell, this traffic control operator can increase, reduce, or even stop traffic (blood flow) completely. This traffic control mechanism is, of course, a small (precapillary sphincter) circular muscle, which can constrict or dilate and thereby reduce or increase the flow of (blood) traffic. Fortunately for the cell we

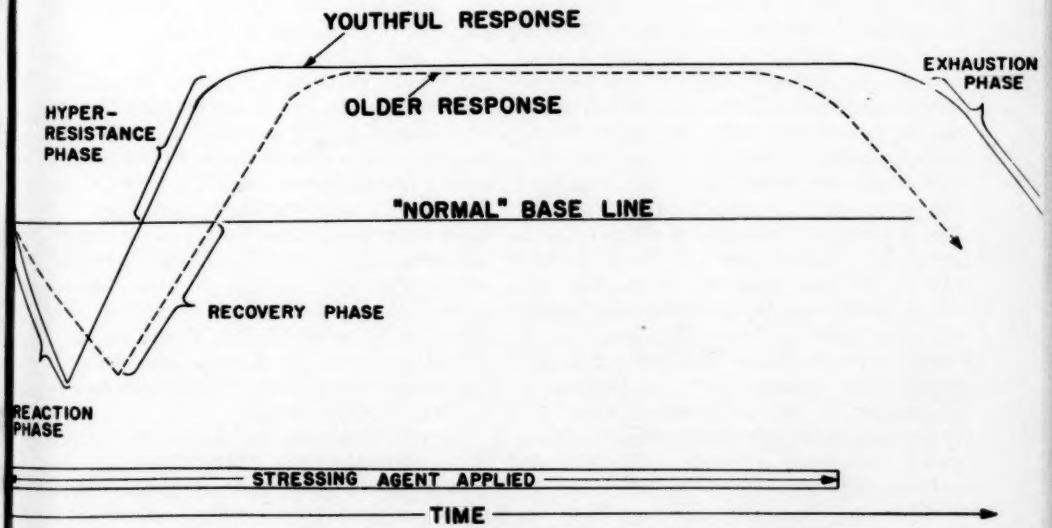


FIG. 2.—Comparison of young and old response to chronic stressing agents.

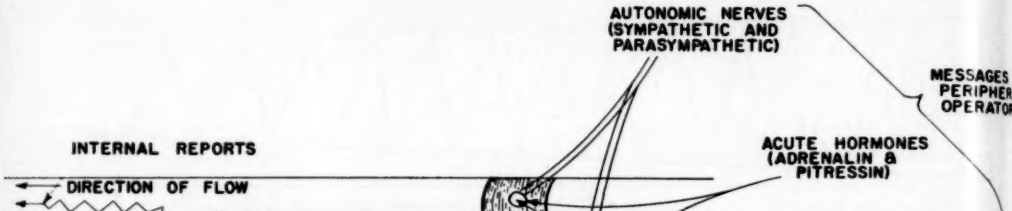


FIG. 3.—Cell's-eye view of life.

are talking about, complete stoppage has never occurred for very long, so it has never suffered anything worse than mild hunger. But the potentiality of starvation obviously exists.

Another source of "worry" is the fact that at times the highway may get overloaded with unneeded quantities of useful or even with harmful chemical objects. When this occurs, some of these may spill over into and accumulate in the cell's pool. Such chemical substances, perhaps entirely harmless when present in normal amounts, can become awful nuisances and even may threaten the life of the cell when they pile up in chronically excessive amounts. Sometimes this causes the pool to get pretty thick and then the movement of oxygen, food, and metabolites is impeded. This state of affairs reminds us of the gardener who is happy to have a few insects and birds in his garden, but whose garden can be destroyed if too many of them enter it. From the standpoint of stress, it is the chronic hormone substances which most concern the cells. Perhaps in prolonged periods of excessive stress the enzyme operators get overwhelmed with too many work orders. Perhaps a kind of chemical confusion results.

These cell "worries" are very real, for there is so very little the cell can do about them except to "worry." The flow of traffic, as well as the amounts of the different materials flowing down the highway, is beyond the control of the cell. The only way the cell can modify its environment is indirectly by sending out its metabolic wastes which serve to advise central headquarters of the state of affairs at the peripheral cell level. These reports may or may not be heeded, depending on the general needs of the organism as a whole.

In this narrow sense the life of the individual cell does not extend beyond its interstitial pool. Yet it is influenced by its environment and by means of its "feed-back messages" it is able to report to the central control headquarters and so it may influence its own environment indirectly. We must never forget that the life of the organism as a whole depends on the successful coordination by means of this control system of the billions of individual cells which make up our bodies. Therefore, individual cells often are sacrificed for the general good of the billions of cells which constitute the whole organism.

Now I have let one simple round cell stand as a symbol for all the billions of cells of the human body, but we all know that there are actually a hundred or more different kinds of cells in our bodies. But this

is not important for our present purposes. Regardless of differences, all of their individual cell lives are controlled by nerves and hormones through peripheral operators and mechanisms as shown in this schematic simplified picture of a cell and its environment.

Now let us look again at the headquarters in the brain which carries out the remarkable coordination job which makes a single organism out of billions of individual cells. It is a very complex headquarters in detail, but in its essence it is not really so complicated at all. A schematic picture of it is shown in Fig. 4.

There is an Intelligence Division where reports come in both from outside and from inside the organism. Our eyes, ears, nose, and skin pick up the outside reports. The inside reports are of course the metabolic feed-back messages already mentioned, which are constantly being given off by the cells of the body. Internal reports also are carried centrally over autonomic and proprioceptive pathways. Specialized statistical clerk cells (in appetite, thirst, and other centers) are constantly receiving and counting these internal and external reports, and in some manner issuing statistical summary reports to the integrating and coordinating units in the message center (vasomotor, respiratory, and other nuclei). Here, the various reports are digested, integrated, weighed and analyzed. Final decisions are made, translated into work order messages and transmitted by the code clerk cells over the various message channels which the organism possesses.

It may ultimately prove to be oversimplified but at present we can identify three kinds of messages to the operators in the field: (1) those which travel over the

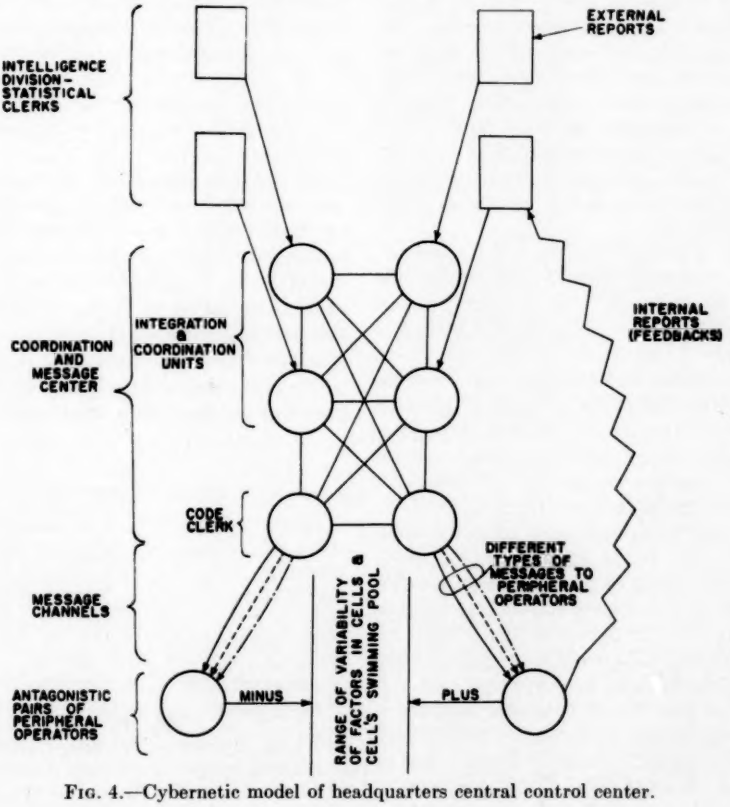


FIG. 4.—Cybernetic model of headquarters central control center.

autonomic nervous system to the capillary operators which direct the traffic control muscles (pre-capillary sphincters) which regulate the capillary traffic of specific cells; (2) those fast-acting endocrines like adrenalin, which can act only at those same points where the muscle operators possess special receivers (autonomic myoneural junctions), and (3) those slow-acting endocrines like the hormones of the thyroid, adrenal cortex and sex glands which can act on the chemical enzyme operators found in all cells and in their interstitial pools.

Through these three basic mechanisms, the lives of individual cells, groups of cells, and the cells of the whole body are ordered, controlled, and regulated for the benefit of the organism as a whole.

As pointed out in my previous aging theory paper, it does no good in complex decision-making if the information needed comes too late to be used. So, it is in this vital center. The statistical clerks, the integrating cells, and code clerks must all do their jobs and they must send their messages and reports to ARRIVE ON TIME. It may be, as suggested in that paper, that the basic physiological defect of aging is an increase in the message transmission time in the central headquarters. Such an event would account for:

1. The increased autonomic nervous-endocrine reaction time which is the one characteristic change seen in many, if not all, physiological activities in which time is measured.

2. The decreased capacity for fine coordination by way of the autonomic nervous-endocrine system in senescence, especially under conditions of extensive stress and for

3. The lessened capacity of the older organism to resist disease and death.

So far our focus has been an organismal aging for that is the kind of aging which interests us. None of us minds losing a few cells, more or less—after all, we lose millions every day. But cybernetics has taught us that the most vital area of a complex system involving feed-backs to a control center is the control area itself. In higher organisms the hypothalamus, and related control and integration nuclei, form such a center and so are our most vital cells. Thus, our interest focuses on the cells of this area. What could occur in these cells which would account for the physiological changes we have noted?

Now the histologists tell us that the cells of the nervous system do not "turn over." (Muscle cells also do not "turn over.") They are never replaced as are the cells of most other tissues (3). An interesting aging experiment reported in 1930 by Sonneborn (4) caused me to wonder if some of the chemical materials of our nerve cells might also not turn over. Sonneborn studied a species of flat worm which reproduces asexually by dividing itself into an anterior and posterior half. He found that the longevity of posterior halves which had to develop new heads greatly exceed the longevity of anterior halves which had only to develop new tails.

It occurred to me that this difference in longevity in the worms might be due to a basic difference in the "vitality" of the stable materials of the homeostatic control center cells. The newly formed control center cells of the posterior halves being more "vital" more "reactive" than the cells of the older control cells of the anterior halves because the former ones were made of new materials.

To test this idea in mammals, a litter of mice was produced with C_{14} labeled proteins by feeding the dam C_{14} labeled glycine and serine during the last six days of pregnancy and the first 12 days of lactation. The young were then killed at various intervals and their tissues were separately analyzed. The experiment (5) is summarized in Table 1.

The principal conclusions which may be drawn from these data are these:

TABLE 1.

	Counts per min. per gram of tissue (wet basis)				
	Dam	S_1	S_2	S_3	S_4
Day Killed	34	18*	34	52	164
Brain	1	22	34	39	25
Heart and lungs	0	30	†	10	13
Liver	13	17	1	2	0
Kidney and spleen	15	33	†	3	0
Skeletal muscle	16	17	7	12	9

* Last day radioactive amino acids were fed.
† These samples were lost through technical error.

(1) The rate of carbon turnover (or preferably "washout") in the sibling brains when administered under the conditions of this experiment was slow indeed as compared with that in liver, kidney and spleen. Whatever the uptake in the dam's brain may have been, there was practically no residual C_{14} by day 34.

(2) Skeletal muscle and the heart and lung aggregate (probably the residual activity here was principally due to heart muscle) also retained considerable radioactivity by day 164. There appears to be greater "washout" in muscle than in brain though this data does not permit too close quantitative comparisons of this kind.

(3) In line with much evidence from histological and chemical studies, liver, kidney, and spleen did turn over their carbon so rapidly that by day 164 no detectable C_{14} remained.

Because it has been demonstrated (6) in plant cells that nuclear material is absolutely stable and not undergoing turnover, it is inviting to speculate, in the light of the above mouse data, that this is also true of animal cells. Such speculation is encouraged by the well established fact that brain and muscle cells are not replaced after these organs have been fully formed (3).

Such speculation leads one to recall the Folin concept of separate endogenous and exogenous protein turnover, recently reviewed by Mitchell (7). It appears that those organs whose cells are constantly dying and being replaced would exhibit both types of turnover but nerve and muscle cells which normally are not being destroyed and replaced would show only exogenous turnover.

Further studies of this design, now under way, should identify the cellular location of and nature of this stable material and also indicate the precise degree of its stability. When this work is complete, we may, assuming the basic aging theory is correct, have narrowed the problem of understanding organismal aging down to that of learning: What could be happening chemically to these static brain (and muscle) proteins which could account for the physiological aging changes observed?

These possibilities seem reasonable:

(1) That some kind of internal bonding occurs (perhaps purely as the result of the passage of time) in the proteins of the cells of this area which make them less chemically reactive to the various information inputs coming into these headquarter cells. Bjorksten (8) has discussed the possibilities of "cross-linkages" between proteins as a cause of aging.

(2) That bombardment of these stable cells by cosmic (or other) rays gradually reduces the number of control cells by destroying some of them—thus, reducing the cellular reserve (redundancy) of the system. Possibly such rays might also damage the stable material of some cells without actually killing them, but leaving them in a less reactive state.

(3) That each memorized "bit" of information is a chemical event which reduces the reactivity of the system by so much. Certainly the total amount of all forms of remembered information increases with living. Not only do our minds contain an increasing amount of information which may be recalled to consciousness. But in the present context, we may look at such activities as conditioning and antibody formation as forms of unconscious memory.

LITERATURE CITED

(1) STILL, JOSEPH W. *Are organismal aging and aging death necessarily the result of death of vital cells in the organism?* Med. Ann. District of Columbia **25:** 199. 1956.

(2) SELYE, HANS. *Stress.* Acta Inc. 1950.

(3) LEBLOND, C. P., and WALKER, B. E. *Renewal of cell populations.* Physiol. Rev. **36:** 255. 1956.

(4) SONNEBORN, TRACY. *Genetic studies on* Stenostomun incaudatum. Journ. Exp. Zool. **57:** 57. 1930.

(5) STILL, JOSEPH W. *Amino acid turnover in brain compared with turnover in other tissues.* Journ. Heredity **48** (5). Sept.–Oct. 1957.

(6) TAYLOR, J. H., WOODS, P. S., AND HUGHES W. L. *The organization and duplication of chromosomes as revealed by autoradiographic studies using tritium-labeled thymidine.* Proc. Nat. Acad. Sci. **43:** 122. 1957.

(7) MITCHELL, H. H. *The validity of Folin's concept of dichotomy in protein metabolism.* Journ. Nutrition **55:** 193. 1957.

(8) BJORKSTEN, J. *Cross-linkages in protein chemistry,* Advances in protein chemistry, edited by Anson, Edsall, and Bailey, **6:** 343. New York, 1951.

BOTANY.—*New or noteworthy ferns from Colombia and Ecuador.* A. H. G. ALSTON, British Museum (Natural History). (Communicated by Joseph Ewan.)

(Received June 2, 1958)

The Pteridophyta collections reported on here were made by Prof. Joseph Ewan, of Tulane University, during his field work in Colombia and Ecuador as botanist with the Cinchona Division of the Foreign Economic Administration, 1944–45. The scope of the Government exploration program was described with particular reference to Ecuador by W. C. Steere (Science **101:** 177–178. 1945, and Sci. Monthly **61:** 114–126. 1945). Professor Ewan collected 1,367 numbers of vascular plants in Colombia and Ecuador, chiefly in the Departamento de Nariño and the Intendencia de Putumayo, Colombia, and the vicinity of Quito, Ecuador. Twenty-seven collections of the total constitute the bases of newly described species published by various authors. Nearly one-third of all the Ewan collections were Pteridophyta (427 numbers), of which 345 numbers have been studied by the present author. The types of the new species described in this paper are in the British Museum (Natural History) (BM), though the prime set is in the U. S. National Herbarium (US), and partial sets in the Instituto de Ciencias Naturales, Bogotá, Colombia (COL), Tulane University, New Orleans (NO), the Gray Herbarium (GH), and the University of California, Berkeley (UC).

GLEICHENIACEAE

Gleichenia Sm.

Gleichenia melanoblasta Alston, sp. nov.

Species ex affinitate Gleicheniae longipinnulae Hook., sed venulis majus approximatis differt.

Rhizomatibus repentibus, elongatis, ca. 2 mm crassis, glabris, protostelicis; rhachidibus subteretibus, tenuiter puberulis, apicem versus ca. 2 mm in diametro, dichotomis, apice inter pinnis dichtomiae alabastro nigro-squamato terminato; squamis, nigrescentibus ca. 1.25 mm longis, 0.4 mm latis, lanceolatis, acuminatis, opacis, crebre ciliato-dentatis, pinnis ultimis ca. 30 cm longis, 3.5 cm latis, pedunculatis; pendunculis ca. 1.25 cm longis, vel sessilibus et subtus dichotomias continuatis; rhachidibus subtus paleaceis, paleis alabastrium similibus; segmentis ultimis usque ad 18 mm longis, 3 mm latis, oblongo-linearibus, apice rotundatis, basi adnatis, sinubus ca. 2 mm separatis, supra subglabris, subtus squamulis irregulariter stellato-laciniatis indutis, numquam glaucis, costis supra tenuis, sparse squamulosis, leviter impressis, subtus crassioribus, prominentibus; venulis parallelis, basi unifurcatis, liberis, supra impressis, subtus prominentibus, vix ad marginem attingentibus, ca. 0.25 mm inter se distantibus; soris plerumque 3–4 sporangia gerentibus, fere costalibus; sporangiis 0.4 mm longis; annulo ca. 20 cellulato; sporis monoletis, anguste fabiformibus, ca. 37 μ longis, laevibus.

COLOMBIA: Putumayo: Quebrada Blanca, along camino Precipicio, Río Afiladores, 2,130 m, *Ewan* 16280 (BM, holotype).

This species bears some resemblance to *Gleichenia blepharolepis* Sod., but it is pubescent below, and to *G. leucocarpa* Sod., but the segments are more parallel-sided and pubescent below. It belongs to the subgenus *Mertensia* Hook. as defined by Holttum (Reinwardtia **4:** 266. 1957). The specific epithet is from Greek $\mu\epsilon\lambda\alpha\nu\sigma\varsigma$ = black, and $\beta\lambda\alpha\sigma\tau\sigma\varsigma$ = bud.

CYATHEACEAE

Cyathea Sm.

Cyathea anacampta Alston, sp. nov.

Species ex affinitate C. firmulae Domin (Hemitelia firma Bak.) sed differt rachidibus pallide brunneis (nec fuscis) et aculeatis (nec laevibus).

Filix terrestris arborescens, caudice breve; stipitibus aculeatis, frondibus ca. 2 m longis (ex schedula), ca. 1 m latis; rhachidibus ca. 1 cm (in sicco) in diametro, pallide brunneis, distante aculeatis, aliter glabris; pinnis alternis, ambitu anguste oblongo-lanceolatis, apice acuminatis, basi petiolulatis, petiolulis ca. 3 cm longis; pinnorum rhachidibus laevibus, pinnatis, et apice pinnatifida; pinnulis ca. 23 utroque latere, ca. 12 cm longis, 1.5 cm latis, fere ad costam profunde pinnatifidis, costis subtus subglabris, supra minute, dense et appresse puberulis, segmentis ultimis ca. 9 mm longis, 3 mm latis, anguste oblongis, leviter falcatis, subcoriaceis, margine apice versus crenato-serratis, costulis utrinque glabris, venulis ca. 14 utrinque latere, supra in-

conspicuis, subtus majus prominentibus, plerumque furcatis; soris submedialibus, in venulorum bifurcationem gerentibus; receptaculis vix elevatis; indusiis non visis; sporangiis pilis stellatis intermixtis; sporis triletis, ca. 38 μ in diametro, subtriangularibus, laevibus.

COLOMBIA: Putumayo: confluence of Río Ticuanayoy and Río Caquetá, 1100 m, *Ewan* 16801 (BM, holotype).

In addition to *C. firmula* Domin., which differs by its smooth dark rachis, the new species bears some resemblance to *C. lindeniana* Presl, which has larger segments, *C. incana* Karst., which has pubescent costae, *C. mettenii* Karst., which has shorter pinnules and convex segments and to *C. ocanensis* Bak., which has a different texture.

The name is derived from Greek ανα = up, and καμπας = turned, from the concave segments with upturned margins, which in the dried state help to distinguish this species.

Cyathea catacampta Alston, sp. nov.

Species ex affinitate C. Kalbreyeri Bak. sed costis puberulis differt.

Filix terrestris arborescens, 3–5 m alta (ex schedula); rhachidibus basi breviter aculeatis, in parte superiore aculeis minutis indutis, supra puberulis, subtus glabrescentibus, in sicco pallide brunneis; frondibus ca. 70 cm latis, bipinnatis, pinnis alternis ca. 5 cm inter se distantibus, basi aërophoris oblongis, glabris, ad superficiem inferiorem indutis, ambitu anguste lanceolatis, apice acuminatis et pinnatifidis, pinnatis, pinnulorum rhachidibus supra puberulis, subtus squamulis irregulariter laciniatis et aculeis verruciformibus sparse vestitis, ca. 35 cm longis, 12 cm latis, pinnulis ca. 24 utroque latere, ca. 7 cm longis, 1.25 cm latis, anguste oblongis, apice acuminatis, basi oblique truncatis, catadromicis, subsessilibus, fere ad costam pinnatifidis, costis supra crebre puberulis, subtus puberulis et plusminusve squamosis, segmentis ultimis ca. 8 mm longis, 2.5 mm latis, anguste oblongis, subacutis, leviter falcatis, coriaceis, margine leviter crenata, costulis supra glabris, subtus squamosis, squamulis nonnullis albidis bullatis indutis; venulis utrinque inconspicuis, ca. 10 utroque latere, bifurcatis; sori medialibus in venulorum bifurcationem gerentibus; receptalculis elevatis pilosis indusiis conspicuis, membranaceis; sporis triletis, ca. 50μ in diametro, grosse verrucosis.

COLOMBIA, Nariño: in Chusquea thickets, between Río Miraflores and Río San Martín, Volcán de Cumbal region, 2,680 m, *Ewan* 16153 (BM., holotype).

The rachis is lacking in the type of *Cyathea Kalbreyeri* Bak., but that species appears to differ by the completely glabrous costae above and by having more flat scales on the under surface of the costae. *Cyathea purpurascens* Sod. has some toothed black scales on the costa, and *C. cystolepis* Sod. bullate white scales.

Cyathea ewanii Alston, sp. nov.

Species ex affinitate Cyatheae choricarpae (Maxon) Domin sed differt costis, hic et ille squamis peltatis albidis instructis, soris medialibus (nec inframedialibus), indusiis fugaciis et sinubis minus profundis.

Caudice non viso, frondibus 2.0–2.5 m longis (ex schedula), ca. 45 cm latis, pinnatis, rhachidibus supra sulcatis, subtus rotundatis et laxe tenuiter lanuginosis, mox glabrescentibus; pinnis suboppositis, ca. 7 cm inter se distantibus, anguste oblongis, sessilibus, patentibus vel leviter ascendentibus, basi supra truncatis, subtus rotundato-truncatis et brevioribus, ca. 23 cm longis, basi 2.2 cm, et supra mediam 4 cm latis, lobatis, lobis basi 9 mm latis rotundatis, leviter crenatis, sinubis ca. 7 mm profundis; costis costulisque utrinque elevatis, supra glabris, subtus glabrescentibus et squamis albidis nonnullis instructis; venulis utrinque elevatis, prope costis costulisque anastomosantibus, utrinsecus 9–10 sed loborum apices versus furcatis nec anastomosantibus; soris in lineis medialibus vel vix supramedialibus, crebre dispositis, uniseriatis subtus sinus continuatis; indusiis desinentibus; receptaculo capitato, setulifero; sporangiis subsessilibus, obovoideo-trapezoidalibus; sporis ca. 20 μ in diam., triletis, a dorso subtriangularibus elongato-areolatis.

COLOMBIA: Putumayo: Common in wet ground between Mocoa and Urcusique on the way to Umbria, 900 m, *Ewan* 16729 (BM, type; isotypes, US, NO).

Among the South American species this is most likely to be confused with *Cyathea subincisa* (Kunze) Domin, but the pinnae in that species are much less deeply lobed as in *C. guatemalensis* (Maxon) Domin and the sori are more distant. This species is named after Prof. Joseph A. Ewan, of Tulane University.

Cyathea leucolepismata Alston, sp. nov.

Species ex affinitate Cyatheae ecuadorensi

Domin (Alsophila sodiroi Bak.), sed differt segmentis minus dissectis rhachidibusque distante aculeatibus.

Filix terrestris arborescens, 3–5 m alta (ex schedula), frondibus bipinnatis fere 1 m latis; rhachidibus brunneis, distante aculeatis, aculeis 1.5 m longis, basi 0.75 mm in diametro, rectis, rhachidibus etiam pubescentibus, subtus pilis longis patentibus 1.25 mm longis, basi bulbosis, supra pilis brevioribus densioribus subappressis; pinnis plus-minusve alternis, ca. 8 cm inter se distantibus, ambitu anguste oblongis, apice acuminatis, basi truncatis, bipinnatis, ca. 19 pinnulis utroque latere, apice pinnatifidis, basi-stipitatis, stipitibus ca. 1.5 cm longis; pinnulis ambitu oblongis, 6.5–9 cm longis, 1.3–2 cm latis, apice acuminatis, basi oblique rotundato-truncatis, breviter petiolulatis, stipite ca. 1.25 cm longe, patentibus, supra subglabris, pinnularum costis hirsutis exceptis, subtus praecipue ad costules venulasque longe hirsutis, hic et ille squamulis albidis instructis, profunde pinnatifidis, sinubus ad 1.25 mm ex costas attingentibus; segmentis oblongis, 6–7 mm longis, 3–4 mm latis, crenatis, apice subacutis, venulis c. 8 utroque latere, furcatis, vel simplicibus, liberis; soris supramedialibus, in venulorum bifurcationem gerentibus; receptaculis puberulis; indusiis non visis.

COLOMBIA: Putumayo: Fairly frequent along selva borders, near San Diego de Colorado, between Umbria and Puerto Asis, *Ewan* 16784 (BM, type; isotypes, US, NO).

The figure of *Cyathea jivariensis* (Hieron.) Domin is very similar to this species, but from the description it lacks the white scales on the costae and the rachises are said to be unarmed.

POLYPODIACEAE

Microgramma Presl.

Microgramma acatallela Alston, sp. nov.

Species inter M. piloselloides (L.) Copel. et M. tecta (Kaulf.) Alston, comb. nov. (Polypodium tectum Kaulf. Enum. Fl. 87. 1824), sed differt foliis heteromorphis, sterilibus anguste oblongo-lanceolatis et fertilibus anguste linearibus.

Rhizomatis late repentibus, ramosis, juventute filiformibus, demum robustioribus, in specimenis visis 40 cm longis, sed certe frequenter longioribus, 1–2 mm diametro, ramulis an longis, an brevibus et 1.5–2 cm longis, crebre squamosis; squamulis imbricatis, appressis, ferrugineis, 3 mm longis, 0.5 mm latis, anguste oblongo-linearibus, peltatis, medio rufo-punctatis, integris, cellulis elongatis; frondibus distantibus, patentibus, dimorphis, sterilibus ca. 6 cm longis, 8 mm latis, anguste oblongo-lanceolatis, apice attenuatis, basi cuneatis, supra glabris, subtus squamulis linearibus, basi ampliatis, frugaliter indutis, stipitibus 1.3 mm longis, anguste alatis, costis utrinque conspicuis, subtus distante squamosis, squamulis anguste oblongo-linearibus; venis secondariis conspicuis, anastomosantibus; areolis utrinsecus uniseriatis, oblongis, venulis singulis simplicibus liberis inclusis et ceteros prope marginem parallelos ferentibus; frondibus fertilibus anguste linearibus, soros utrinsecus prope costam uniseriatos ferentibus; seris rotundis, 2 mm in diametro; sporangiis squamulis aciculatis intermixtis glabris, longe stipitatis; stipitibus eglandulosis; annulis 12- cellulatis; sporis monoletis, fabiformibus, 60 μ longis, 45 μ latis, crebre verrucolosis.

COLOMBIA: Putumayo: 3 kilometers above Mocoa, on trail to San Antonio, 600 m, epiphytic, *Ewan* 16706 (BM, type; isotypes, US, NO); between Puerto Asis and confluence of the Río Guamues with the Río Putumayo, 375 m, epiphytic, *Ewan* 16760 (BM, type; isotypes, US, NO).

PERU: Loreto: Left bank of Río Santiago, above Pongo de Manseriche, on twigs of large forest tree, 200 m, *Mexia* 6144b (BM).

The specific name is taken from the Greek ακαταλλελος = heterogeneous, on account of the heteromorphous fronds which separate this plant from *M. piloselloides* (L.) Copel.

THELYPTERIDACEAE

Goniopteris Presl.

Goniopteris fendleri (Eat.) Alston, comb. nov.
Aspidium fendleri Eat., Mem. Amer. Acad. new ser. **8:** 210. 1860; *Dryopteris fendleri* (Eat.) O. Kuntze, Rev. Gen. Pl. **2:** 812. 1891; C. Chr., K. Danske Vid. Selsk. Skrift. **10** (2): 173. f. 23. 1912.

COLOMBIA: Nariño: Quebrada Ensillada near Altaquer, Río Guabo, 3400 m., *Ewan* 16810. Previously recorded from Colonia Tovar, State of Aragua, Venezuela.

Thelypteris Schmidel

Subgenus **Lastrea** (Bory) Alston, comb. nov.
Lastrea Bory, Dict. Class. Hist. Nat. **6:** 588. 1824, and **9:** 232. 1826, p. p.
Dryopteris subgenus *Lastrea* (Bory) C. Chr. in Rosenv. Bioi. Arb. til. Warming 79. 1911.

Thelypteris bonapartii (Ros.) Alston, comb. nov.
Dryopteris bonapartii Ros. in Fedde Repert. **7:** 303. 1909; C. Chr., K. Danske Vid. Selsk. Skrift. **10** (2): 146. f. 16a. 1912.

COLOMBIA: Nariño: Near summit of Cordillera Oriental, above Río de Potreros, headwaters of Río Tellez, 3,200–3,400 m, *Ewan* 16527. Previously known from Ecuador.

Thelypteris brausei (Hieron.) Alston, comb. nov.
Dryopteris brausei Hieron. in Hedwigia **46:** 337. t. 6, fig. 11. 1907.

ECUADOR: Carchi: near Pun, Río Chingual, *Ewan* 16313. Originally described from Colombia (valley of Río Paez, Cord. Central, Tolima region, *Stübel* 145).

Thelypteris caucaensis (Hieron.) Alston, comb. nov.
Nephrodium caucaense Hieron. in Engl. Bot. Jahrb. **34:** 444. 1904.
Dryopteris caucaensis (Hieron.) C. Chr., K. Danske Vid. Selsk. Skrift **4** (4): 286. fig. 13. 1907; **10** (2): 139. 1912.

COLOMBIA: Nariño: San José, Río Chingual, below Victoria, 2,650 m, *Ewan* 16211. The stipes are more pubescent than in the type collection (*Lehmann* 3102) as represented in the British Museum.

Thelypteris elegantula (Sod.) Alston, comb. nov.
Nephrodium elegantulum Sod. Crypt. Vasc. Quit. 243. 1893; C. Chr., K. Danske Vid. Selsk. Skrift. **10** (2): 156. 1912.

COLOMBIA: Nariño: 18 kilometers above Pasto on Tangua road, 2,700 m, *Ewan* 15923.
ECUADOR: Carchi: 5 kilometers south of Tulcán, Altos de Boliche, 2,960 m, Ewan 16300. I refer these specimens to this species with some doubt; it was originally described from the Pallatanga Valley, about Puente de Chimbo, western Cordillera of Ecuador.

Thelypteris funckii (Mett.) Alston, comb. nov.
Aspidium funckii Mett., Ann. Sci. Nat. ser. 5. **2:** 246. 1860.
Dryopteris funckii (Mett.) O. Ktze. Rev. Gen. Pl. **2:** 812. 1891; C. Chr., K. Danske Vid. Selsk. Skrift. **4**(4): 299. 1907; 10(2): 139. 1912.

ECUADOR: Pichincha: Corazon Peak, 2,800 m., *Ewan* 16420. Recorded from Costa Rica, Venezuela, Colombia, and Peru, but I have seen no published record from Ecuador. The characteristic scales on the rachis are deciduous but present on the young fronds.

Thelypteris lanipes (C. Chr.) Alston, comb. nov.
Dryopteris lanipes C. Chr., Smithsonian Misc. Coll. **52:** 394. 1909; K. Danske Vid. Selsk. Skrift. **10**(2): 153. 1912.

COLOMBIA: Putumayo: near Quebrada Patayaco, Río Mocoa, 2,100 m, *Ewan* 16669. This species was originally described from Guatemala and the specimen is placed here with some doubt.

Thelypteris lepidula (Hieron.) Alston, comb. nov.
Dryopteris lepidula Hieron., Hedwigia **46:** 328. t. 4, fig. 4. 1907; C. Chr., K. Danske Vid. Selsk. Skrift. **4**(4): 281. 1907; **10**(2): 137. 1912.

COLOMBIA: Nariño: 3 kilometers above San José, on trail to Las Mesas via Quebrada San Francisco, 2,700 m, *Ewan* 16566. Ewan's plant has a few scattered hairs on the surface of the lamina, which are lacking in the type collected by *Stübel* 332 at Miraflores, 2,700 m.

Thelypteris lindigii (C. Chr.) Alston, comb. nov.
Dryopteris lindigii C. Chr. Ind. Fil. 275. 1905; Hieron., Hedwigia **46:** 328. 1907; C. Chr., K. Danske Vid. Selsk. Skrift. **4**(4): 282. 1907.

COLOMBIA: Nariño: Avenida de las Jajas, Ipiales, 2,835–2,895 m., *Ewan* 16127.

Thelypteris muzensis (Hieron.) Alston, comb. nov.
Dryopteris muzensis Hieron., Hedwigia **46:** 331. t. 4. fig. 6. 1907; C. Chr., K. Danske Vid. Selsk. Skrift. **4**(4): 280. 1907; Smithsonian Misc. Coll. **52:** 373. 1909.

COLOMBIA: Nariño: 2 kilometers above San Juan, *Ewan* 16030.

Thelypteris pachyrachis (Kunze) Proctor, Bull. Inst. Jamaica **5:** 62. 1953.
var. **bogotensis** (C. Chr.) Alston, comb. nov.
Dryolteris pachyrachis var. *bogotensis* C. Chr., K. Danske Vid. Selsk. Skrift. **4**(4): 306. 1907.

COLOMBIA: Antioquia: Quebrada San Julian, between Argelia and 'El Tigre', 1,800 m, *Ewan* 15782.

Thelypteris piloso-hispida (Hook.) Alston, comb. nov.
Nephrodium piloso-hispidum Hook., Spec. Fil. **4:** 105. 1862.
Dryopteris piloso-hispida (Hook.) C. Chr., K. Danske Vid. Selsk. Skrift. **10**(2): 148. 1912.

COLOMBIA: Cauca: 4 kilometers north of Popayan, 1,680 m, *Ewan* 15875. Ranges from Mexico to Bolivia, but Christensen cites no specimen from Colombia.

Thelypteris scalaris (Christ) Alston, comb. nov.
Aspidium scalare Christ in Bull. Herb. Boiss. ser. 2. **6:** 159. 1905.
Dryopteris scalaris (Christ) C. Chr. in K. Danske Vid. Selsk. Skrift. **4**(4): 323. fig. 47. 1907.

COLOMBIA: Cauca: 4 kilometers north of Popayan, 1,680 m. *Ewan* 15876. Recorded from Mexico to Costa Rica.

Thelypteris tablaziensis (C. Chr.) Alston, comb. nov.
Dryopteris tablaziensis Christ in Bull. Herb. Boiss. ser. 2. **7:** 262. 1907; C. Chr. in K. Danske Vid. Selsk. Skrift. **4**(4): 278. fig. 6. 1907; **10**(2): 136. 1912.

COLOMBIA: Antioquia: Foot of Santa Elena, 2 kilometers east of Medellín, 1,800–2,100 m, *Ewan* 15696. Previously known from Costa Rica and Panama.

Subgenus **Glaphyropteris** (Presl) Alston, comb. nov.
Glaphyropteris Presl in Abh. Bohm. Ges. Wiss. ser. 5. **5:** 344. 1848.
Dryopteris subg. *Glaphyropteris* (Presl) C. Chr. in Ros. Biol. Arb. til Warming 80. 1911.

Thelypteris cañadasii (Sod.) Alston, comb. nov.
Nephrodium cañadasii Sod. Rec. Crypt. Vasc. Quito 48. 1883; Crypt. Vasc. Quit. 236. 1893.
Dryopteris cañadasii (Sod.) C. Chr. Ind. Fil. 256. 1905; Hieron. in Hedwigia **46:** 339. 1907; C. Chr. in K. Dansk. Vid. Selsk. Skrift. ser. 4. **4:** 322. fig. 44. 1907; **10**(2): 158. 1912.

ECUADOR: Pichincha: Corazon, 2,800 m, *Ewan* 16424. The type was from the Hacienda Niebli at 2,000 m on the western slope of Volcán Pululahua, Chimbarazo region, Ecuador.

Thelypteris mapirensis (Ros.) Alston comb. nov.
Dryopteris mapirensis Ros. in Fedde Repert. **6:** 315. 1909; C. Chr. in K. Danske Vid. Selsk. **10** (2): 189. fig. 18. 1910.

COLOMBIA: Nariño: Quebrada Ensillada, near Altaquer, Río Guabo, 3,400 m, *Ewan* 16811. This species has been previously recorded as from Bolivia.

ATHYRIACEAE

Diplazium Sw.

Diplazium subnudum (Karst.) Alston, comb. nov.
Asplenium subnudum Karst. Fl. Colomb. **2:** 93. t. 148. 1865.
Asplenium lindbergii Mett. in Ann. Sci. Nat. ser. 5. **2:** 236. 1864, pro parte quoad plantae andina.

COLOMBIA: Putumayo: Río Mocoa, between Sachamate and San Antonio, 1,700 m, *Ewan* 16699. The Andean specimens are more deeply lobed than the typical *Diplazium lindbergii* (Mett.) Christ of Brazil.

ASPIDIACEAE

Rumohra Raddi

Rumohra trianae (Mett.) Alston comb. nov.
Aspidium trianae Mett. in Ann. Sci. Nat. ser. 5. **2:** 243. 1864.
Dryopteris trianae (Mett.) O. Kuntze, Rev. Gen. Pl. **2:** 814. 1891; C. Chr. in K. Danske Vid. Selsk. Skrift. **6**(1): 109. 1920.

COLOMBIA: Nariño: Quebrada La Toma, on Río Telembi, between Río Pimbi and Río Cuembi, above Barbacoas, 70 m, *Ewan* 16861. The type specimen was from Via de Tuquerres, Barbacoas, *Triana* 32, which Christensen wrongly attributed to Venezuela. It must have been taken in the same general area as Professor Ewan's locality. This species has also been recorded from Peru.

Polystichum Roth

Polystichum mexiae Copel.

COLOMBIA: Putumayo: Near Quebrada Patayaco, between San Francisco and Sachamate, 2,100 m, *Ewan* 16671. The type collection, *Mexia* 7679, was from Mount Pichincha in Ecuador. It has more scales on the rachis, but these are probably deciduous.

LOMARIOPSIDACEAE

Elaphoglossum Schott

Elaphoglossum ambiguum (Mett.) Alston, comb. nov.
Acrostichum ambiguum Mett. ex Christ in Denkschr. Schweiz. Natur Ges. **36:** 60. 1899.

COLOMBIA: Santander: 5 kilometers northeast of Charala, 2,300 m, *Ewan* 15663. The three species, *Acrostichum compactum* Mett., *A. fendleri* Mett., and *Elaphoglossum sporadolepis* (Kunze) Moore, are similar, but as *Acrostichum ambiguum* Mett. appears to be the best match, that epithet seems preferable.

POSTSCRIPT

Arthur Hugh Garfit Alston died on March 17, 1958, in Barcelona, Spain, while on a holiday. He had been in poor health in recent years. During 1954–55 Mr. Alston traveled and collected in Indonesia toward the preparation of an account of the Pteridophyta for the *Flora Malesiana*.—J.E.

ZOOLOGY.—*A new family of millipeds on Barro Colorado Island, Canal Zone.*

H. F. LOOMIS, Miami, Fla.

(Received May 16, 1958)

On June 6, 1923, the writer accompanied the late Dr. O. F. Cook, of the U. S. Department of Agriculture, on a visit of several hours to Barro Colorado Island, in the Canal Zone, for the purpose of seeing that newly designated wildlife preserve, studying a few of its palms, and collecting millipeds. A number of the latter were found, and in identifying them some months later in the United States a single female was noted that appeared to belong to one of the families, of the order Merocheta, whose members are capable of rolling themselves into a near perfect sphere when disturbed. Closer inspection, however, revealed characters that seemed to prohibit its inclusion in any of the known families, and it was put aside to await collection of additional specimens, especially males, so that its classification might be more exact.

In the years that followed, attempts were made through written and oral appeals to scientists stationed or visiting in the Canal Zone to have the species recollected, but these failed. However, in the spring of 1958 the writer and his wife were able to spend a week collecting on Barro Colorado, and some additional time elsewhere in the Canal Zone and in several Panamanian localities. In spite of the very dry conditions encountered nearly everywhere, fair numbers of millipeds were found, among them being two immature specimens of the desired form, discovered by Mrs. Loomis in a decaying palm inflorescence on the ground near the Shannon Trail on Barro Colorado. While these two specimens, together with the original female, may not form the best material on which to base a new family, its characters are readily seen and are so distinctive it cannot be confused with any previously established family. Accordingly, a description of it is presented.

Dorsoporidae, n. fam.

Description.—Body small, strongly convex, about four times as long as broad, smooth and shining and capable of being tightly rolled; its sides vertical, with lateral carinae produced downward but an even shorter distance than are those of the Cyclodesmidae.

Head hispid below the vertex; labrum broad, with margin straight and having the usual three median teeth; antennae rather stout and subclavate.

First segment trapezoidal; second segment much larger than any other, of the shape of the third segment in the family Cyclodesmidae; ensuing segments without a sulcus crossing the dorsum but with a distinct longitudinal sulcus separating the lateral carinae from the dorsum; pores in normal sequence, opening high on the sides of the dorsum and far removed from the lateral carinae; segments without a supplementary margin; last segment short and broad but not as broad as the margin of the penultimate segment on either side of it; lateral carinae of segments 5 to 14 with a tuberclelike process projecting downward from near the middle of the inner surface, its apex separated from the carina wall by a deep sinus into which the margin of the next carina appears to fit when the body is rolled.

The most striking character of this new family, and one which will instantly identify it, is the presence of repugnatorial pores in normal sequence, not on the lateral carinae, as in any other family of the order having pores, but high on the sides of the dorsum itself.

It is doubtful if the systematic position of the family can be determined until males are examined. On other characters, the enlarged second segment, associated with the presence of repugnatorial pores, might indicate relationship with the Oniscodesmidae, but in that family the segments are divided into two sections by a transverse sulcus that is not indicated in the Dorsoporidae and the lateral carinae are very oblique, extend much further from the body and support the pores. The smooth, strongly convex dorsum without a transverse sulcus across the segments, vertical sides and rather small, descending lateral carinae are characters common to the Cyclodesmidae and the Dorsoporidae but the presence of pores; carinae separated from the

dorsum by a sulcus; and the second segment being enlarged, rather than the third, distinguish the latter family.

Dorsoporus, n. gen.

Genotype: *Dorsoporus barroensis,* n. sp.

Description.—Body relatively broad and capable of being rolled into a compact ball; dorsum strongly convex with vertical sides; surface smooth and shining.

Head hispid from the labrum to the upper limits of the antennal sockets above which it is smooth and shining; median groove of the vertex very faint; antennae rather stout, subclavate, hispid; joints 2, 3, 5, and 6 subequal in length with joint 4 shorter.

First segment trapezoidal; anterior margin with a raised rim; posterior margin simple, somewhat shorter and overlapping the anterior margin of the second segment between the lateral lobes; lateral margins oblique, nearly straight.

Second segment greatly expanded on the sides in front and below, similar in appearance to the third segment of *Cyclodesmus,* obscuring the head and some of the first segment in lateral view (Fig. 1).

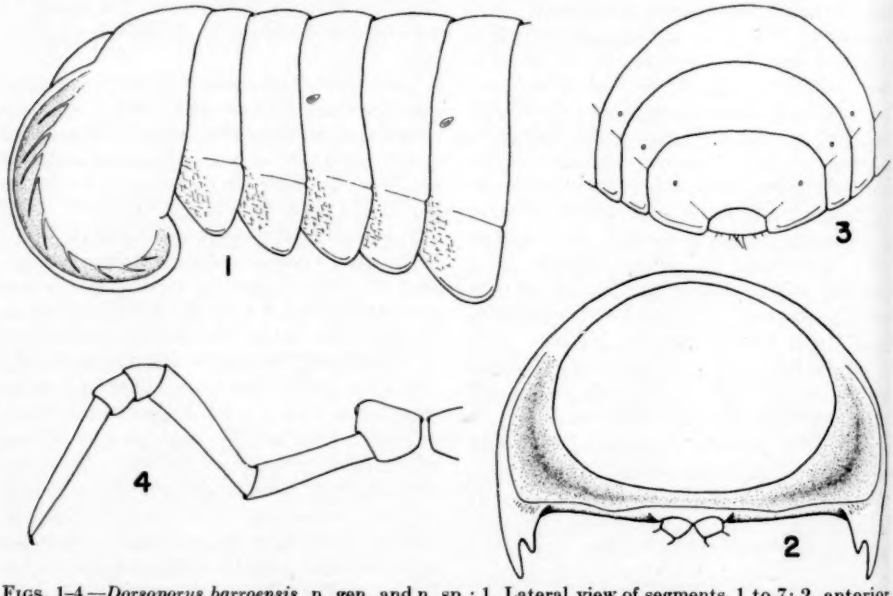
Ensuing segments, including the penultimate, without a transverse sulcus or supplementary margin but with lateral carinae separated from the dorsum by a distinct sulcus extending forward from a small notch located in the posterior margin far below the line of the pores; lateral carinae of segments 5 to 14 each with a descending process elevated from the surface on the inner side near the middle, as shown in Fig. 2, and in the sinus formed between the carina and the process the edge of the carina of the next segment rests when the body is rolled.

Pores arranged in normal sequence, beginning on segment 5 and ending on segment 19, but placed high on the sides of the body, far above the lateral carinae although approaching them on segments 18 and 19.

Last segment rather small, transverse, not as broad as the carinae of the penultimate segment, the margin nearly straight and simple (Fig. 3).

Legs long and very slender, capable of reaching well beyond the sides of the body; joints 2, 3 and 6 subequal in length, each about double the length of joints 4 and 5 combined; sterna very narrow (Fig. 4).

Males unknown; females with the ventral surface of the third segment developed behind the legs into a conspicuous triangular lobe projecting over the sternum of the next pair of legs.



FIGS. 1–4.—*Dorsoporus barroensis,* n. gen. and n. sp.: 1, Lateral view of segments 1 to 7; 2, anterior view of segment 12; 3, segments 17 to 20 from behind; 4, first leg of segment 6.

Dorsoporus barroensis, n. sp.

One female (type) collected June 6, 1923, by O. F. Cook and H. F. Loomis, and two immature specimens (paratypes) collected March 16, 1958, by E. M. and H. F. Loomis, all on Barro Colorado Island, C. Z. These specimens deposited in the U. S. National Museum.

Description.—Length of mature female 6 mm, width 1.5 mm.

Head moderately thickly beset with stiff, erect hairs of medium length from the upper limits of the antennal sockets to the labrum; vertex smooth but with a median groove faintly impressed; antennae gradually thickened from the base to the end of the fifth joint, the joints after the first finely hispid, the sixth joint with 2 very long hairs near the distal end; joints 2, 3, 5, and 6 of about equal length, joint 4 slightly shorter.

First segment transverse, trapezoidal, nearly twice as broad as long; anterior margin considerably longer than the posterior margin, paralleling it and with a raised rim; posterior margin overlapping the front margin of segment 2; anterior lateral angles rather sharply rounded, the posterior ones broadly rounded.

Second segment greatly enlarged, each side produced forward and downward; posterior margin with a definite notch just above the expanded portion on each side; sides of the segment with a raised rim extending from opposite the posterior angle of segment 1 to the notch in the back margin; behind this rim is a broad, concave channel into which project, obliquely downward, long, narrow extensions of the higher surface behind the channel.

Anterior lateral surface of the segments after the second noticeably reticulated on the portion which is hidden beneath the segment in front, when the body is rolled.

Pores and lateral carinae as previously described except that reduced processes are present inside the carinae of segments 3 and 4 but lack the sinus found on ensuing segments.

Last segment relatively small as compared with the penultimate one and not as broad as its carinae; twice as broad as long, the posterior margin slightly rounded and with 7 to 8 setae; anal valves flattened but with raised margins; preanal scale large, over half as long as wide and rounded-triangular.

To produce and multiply endlessly, without ever reaching the last possibility of excellence, and without committing herself to any end, is the law of Nature.—JOHN BURROUGHS.

ZOOLOGY.—*Further notes on* Sarsiella tricostata.[1]

MEREDITH L. JONES, Oceanographic Institute, Florida State University, Tallahassee, Fla.[2]

(Received May 29, 1958)

Recently the description of the ostracod *Sarsiella tricostata* from San Francisco Bay appeared in this Journal (Jones, 1958). By and large it was presented from the zoological standpoint and was based almost entirely on the soft parts of the animal. Subsequent to the publication of the description, the author has had several contacts with paleontologists who stressed the necessity, from their viewpoint, of a detailed description of ostracod hard parts. The present work then, while it makes no alteration of the preceding description, will deal with the structure of the hard parts and will represent an augmentation of the original description. The observations reported here are based on paratype material collected by the author from Point Richmond, San Francisco Bay, Calif., and are part of the series from which the holotype and allotype were chosen. The discussion which follows is based on shell of females, for several reasons. First, a female was designated as the holotype; second, females are more common than males in the field; and third, there are no sexual differences embodied in the characters to be discussed here. Such morphological differences as do exist between males and females are to be found in the species description (Jones, 1958).

A second item concerning the original description is that *Sarsiella* is best considered to be of the family Sarsiellidae rather than of the Cypridinidae.

SHELL-SURFACE ORNAMENTATION

In the previous work on *Sarsiella tricostata* it was implied that the shell surface was smooth, except for the obvious ridges and was covered with fine hairs. Further observations have shown that the fine hairs originate from punctations which are visible under reflected light, and which cover the surface of the shell in the areas between the various ridges (Fig. 1). In addition, there are two pits at the posterior end of the ridge separating the dorsal and the postero-ventral fields.

HINGE STRUCTURE

The hinge of *Sarsiella tricostata* is of the "ridge and groove" type (Fig. 3, *a*, *b*) in which the ridge is on the right valve and the groove on the left. A dorsal flange of the left valve overlaps the right valve (Fig. 2). Immediately below this is the groove which receives the ridge of the right valve.

TYPE MATERIAL

In addition to the distribution of types and paratypes listed in the previous paper (U. S. National Museum; Museum of Paleontology, University of California, Acc. No. 1846; and the British Museum, London), paratypes have been deposited with the Henry V. Howe Collection at the School of Geology, Louisiana State University.

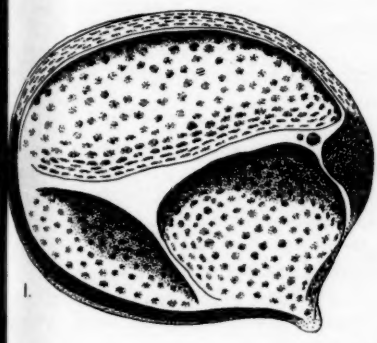
The authors wishes to acknowledge the kind advice and criticism of Dr. Harbans Puri, Florida Geological Survey, Tallahassee, and of Neil C. Hulings, Oceanographic Institute, Florida State University.

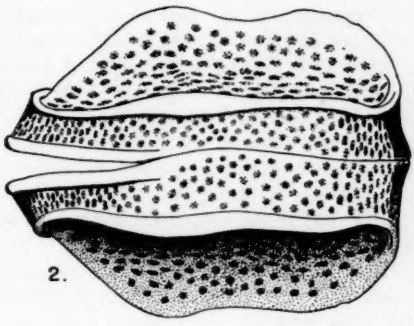
LITERATURE CITED

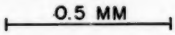
JONES, MEREDITH L. Sarsiella tricostata, a *new ostracod from San Francisco Bay (Myodocopa: Cypridinidae)*. Journ. Washington Acad. Sci. **48:** 48-52. 1958.

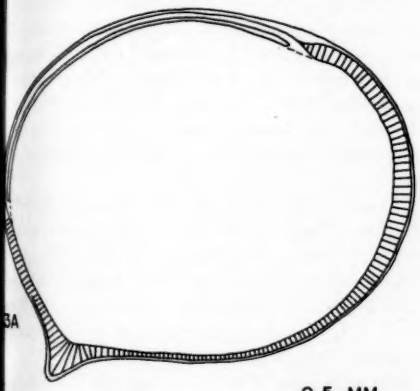
[1] Contribution no. 105 from the Oceanographic Institute, Florida State University.

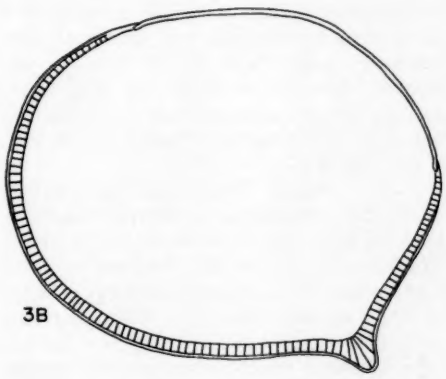
[2] Address: Research Division, U. S. Navy Mine Defense Laboratory, Panama City, Fla.











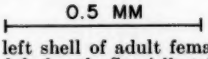


FIG. 1.—Surface view of left shell of adult female *Sarsiella tricostata* (anterior end is to the left).
FIG. 2.—Dorsal view of adult female *Sarsiella tricostata* (anterior end is to the left).
FIG. 3.—Hinge structure of adult female *Sarsiella tricostata*. 3*a*, view of interior of left shell; 3*b*, view of interior of right shell.

ENTOMOLOGY.—Armigeres (Armigeres) baisasi, *a new mosquito from the Philippine Islands (Diptera: Culicidae)*.[1]

ALAN STONE, Entomology Research Division, U. S. Department of Agriculture, and ERNESTINE B. THURMAN,[2] National Institutes of Health, Public Health Service.

In a series of Philippine mosquitoes originally determined as *Armigeres* (*Armigeres*) *kuchingensis* Edwards, 1915, in the collection of the U. S. National Museum, the males differed from *kuchingensis* in the structures of the terminalia, although they appeared as *kuchingensis* in general habitus. Females of the two species may be separated by the presence of a subapical white band on sternite VII in *kuchingensis*, the band being apical in the new species.

Baisas (1935) includes *kuchingensis* in his notes on Philippine mosquitoes and figures the structures of the male terminalia in Plate 3, figs. 1, 3, 5, and 7. Although his description for the most part is applicable to *kuchingensis*, his figures of the structures of the claspette, dististyle, and phallosome do not agree with those of the type in the British Museum as noted by the senior author. We are convinced that Baisas figured the male of *Armigeres* (*Armigeres*) *baisasi*, n. sp. (Fig. 1).

Bohart (1945) lists *kuchingensis* and *Armigeres* (*Armigeres*) *joloensis* (Ludlow, 1904) as synonyms of *Armigeres* (*Armigeres*) *obturbans* (Walker, 1860). We consider both *kuchingensis* (Fig. 2) and *joloensis* (Fig. 3) to be valid species (Thurman, 1958) and distinct from *obturbans* (Both species have a long dististyle which, when pressed against the basistyle, reaches the base of the claspette.); and that *obturbans, sensu stricto*, does not occur in the Philippines, and *kuchingensis* probably does not. *A. obturbans* of Barraud (1934) *et auctorum* (*nec* Walker, 1860; *nec* Bohart, 1945) is *Armigeres* (*Armigeres*) *subalbatus* (Coquillett, 1898), which is the common oriental species distributed from Japan, China, and Taiwan south and west through Thailand to India and Ceylon.

[1] Acknowledgment is made of the support provided by the Division of Research Grants, National Institutes of Health, Public Health Service, D. H. E. W., under Grant E 809 awarded to William E. Bickley, Department of Entomology, University of Maryland.

[2] Sanitarian (R), on detail from the Division of Research Grants, N.I.H.

Armigeres (Armigeres) baisasi, n. sp.

Male.—Medium sized, wing 3.5 to 4 mm.

Head.—Proboscis and palpus dark; palpus longer than proboscis by ½ the length of the last segment. Torus white scaled. Clypeus bare. Vertex covered with white flat scales, few light bronzy scales scattered laterally and medially, few dark upright forked scales at nape.

Thorax.—Mesonotum with dark coppery narrow scales; mesonotal border wide, white; prescutellum with medial white spot extending onto the midlobe of the scutellum, the posterior scales broad. Scutellar setae coppery. Halteres with coppery capitulum and light base. Anterior pronotal lobe, posterior pronotal lobe, fore coxa, and propleuron all white scaled. One lower mesepimeral bristle present. Hind femur with dark stripe on dorsum, white scales to apex on anterior and venter. All tarsi are dark with blue metallic luster. Midclaws equal.

Abdomen.—Tergites dark with coppery metallic luster. Tergite VIII with basal white spot. Sternites II–VI all white scaled. Sternite VII dark basally with apical white band. Lateral white markings form a straight line on tergites II–III (II–IV in some paratypes); tergites IV–VI show slight convexity (semicircles).

Male terminalia (Fig. 1).—Basistyle (Bs) long, slender, 3:1. Dististyle (Ds) short, medially expanded, not reaching base of setae of claspette when pressed against basistyle; 20 teeth on apical half, each tooth with a deep medial groove; apical tooth (Ds-AT) slightly longer than others; 2 or 3 setae on apical third of dorsum. Claspette (Cl) with two sharp setae usually curving toward basistyle, a few finer setae and spiculation on interbasal fold. Phallosome (Ph) with distinct V-shaped division in ventral lobe, the basal portion composed of four processes in graduated sizes and a median process. Ventral surface of dorsal lobe with wavy creases and small crenulations.

Female.—Similar in size and coloration to the male. Palpus nearly one-fourth as long as probos-

cis. White lateral markings on tergites III–VII are small semicircles which may be slightly triangular on IV–V.

Larva and pupa.—We do not describe these at the present time because the quality of the material does not permit accurate descriptions.

Holotype, male, U.S.N.M. no. 64105.

Type locality, Abuyog, Leyte, P. I.; November 1944 (O. H. Graham).

Paratypes.—Three males, one female. data of holotype. One male, Baguio, Luzón; August 26, 1945 (Shields). Three males, San Fernando, La Union, Luzón, P. I., 24 MSU #416; August 2, 1945 (S. E. Shields). One female, Camp Stotsenberg, [Luzon], P. I.; August 15, 1924 (Maj. W. H. Teffs). One female, Camp Stotsenberg, Pampanga, Luzón, P. I. One male and one female, Angeles, Pampanga, [Luzon], P. I. (Dr. Whitmore). Two males, four females, Calicoan Island, P. I.; February 12, 1944 (J. H. Paullus, #109). One male, one female, one larval skin, Leyte Gulf, P. I., #12–9, 4 and #12–23, 3 (J. T. Medler). One female, Leyte, P. I., 32 MSU #368; January 6, 1945. One female, Leyte, P. I., 32 MSU #306; December 19, 1944. One female, Leyte, P. I., APO 72; December 19, 1944 (K. V. Krombein, #306). One male, five females from a series of specimens from Jolo Jolo, without

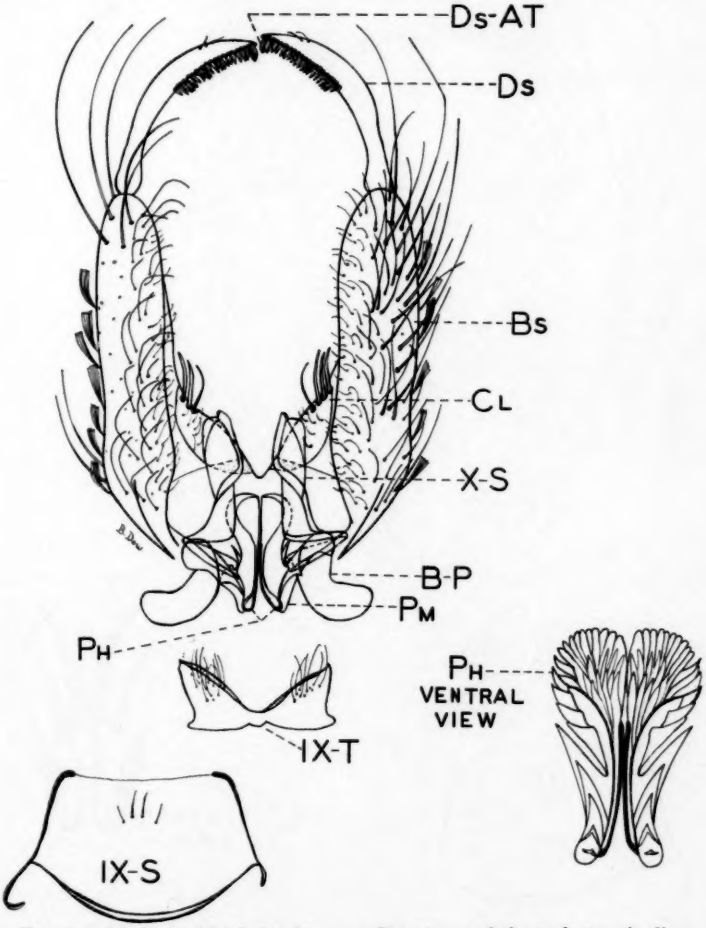


FIG. 1.—*Armigeres (A.) baisasi*, n. sp.: Structures of the male terminalia.

further data. Six males, 14 females, Gandara, Samar, P. I.; February and November. One female, Camp Overton, Mindanao, P. I. One male, P 818, Kalingan, Lanao, [Mindanao]; April 25, 1946, reared from coconut shell (S. A. Edgar, J. Enke, E. Gutierres, and A. Corcega). One female, P-975-3, Lasang, Davao, [Mindanao]; May 2, 1946 (J. Enke, H. Hoogstraal, P. Feliciano, and A. Corcega). One male, P-975, reared from coconut husks, Davao, [Mindanao]; May 7, 1946 (J. Enke, H. Hoogstraal, P. Feliciano, and A. Corcega). One female with larval and pupal skin, P-978-1, Lasang, [Mindanao], reared from fallen coconut leaf in shade; May 7, 1946 (J. Enke, H. Hoogstraal *et al.*). One female, P-996-1, Lasang, Davao, [Mindanao], reared from fallen coconut leaf sheath; May 7, 1946 (J. Enke, H. Hoogstraal *et al.*).

This species is named for Dr. F. E. Baisas of the Division of Malaria, Department of Health

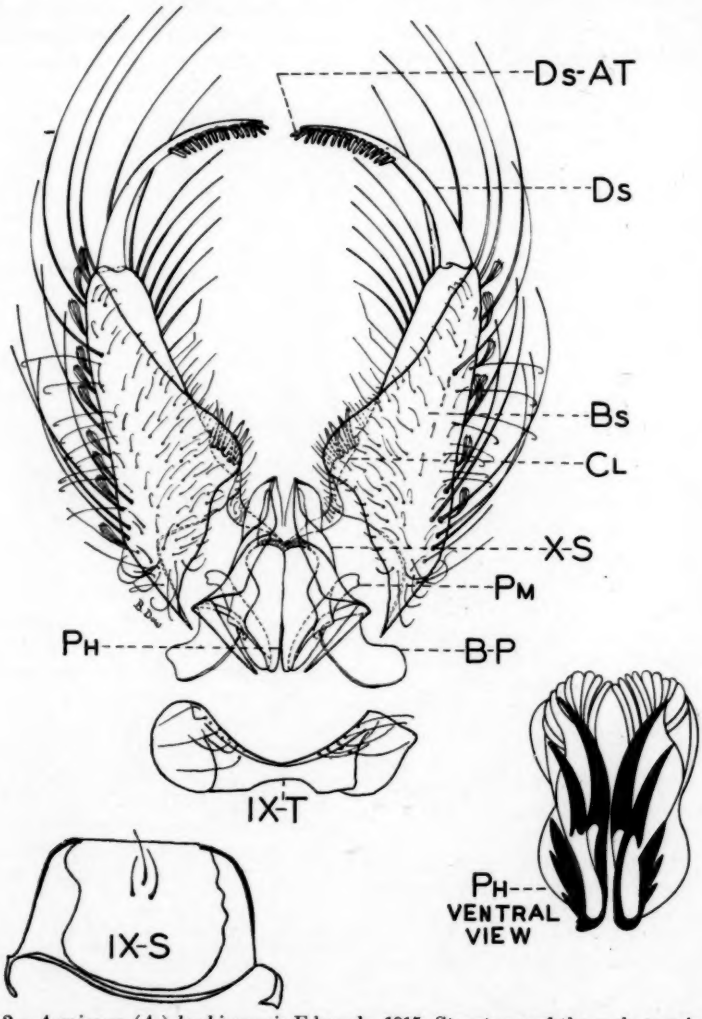


FIG. 2.—*Armigeres* (*A.*) *kuchingensis* Edwards, 1915: Structures of the male terminalia.

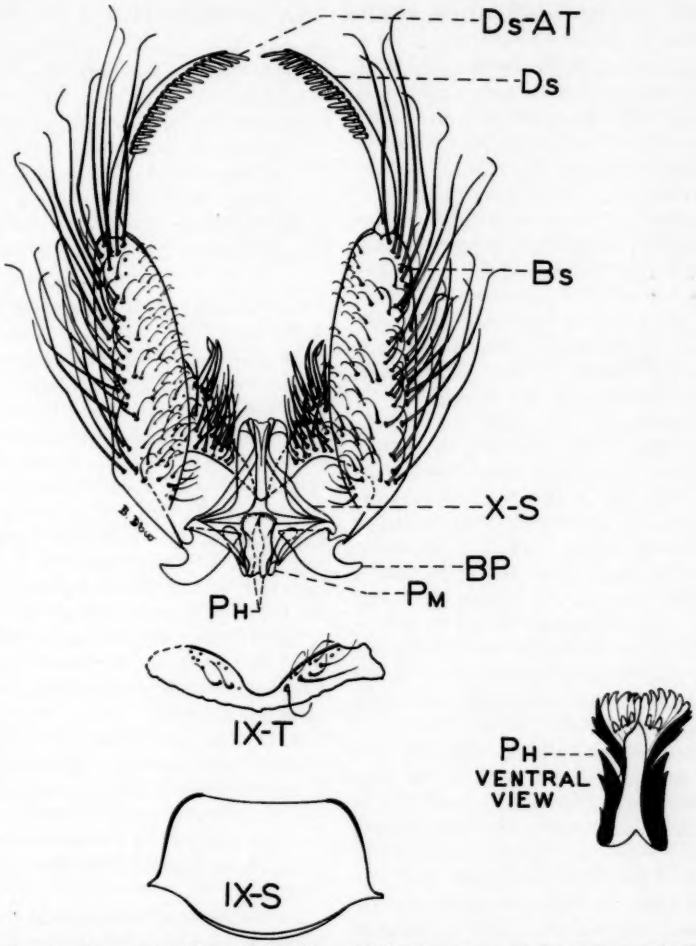


FIG. 3.—*Armigeres* (*A.*) *joloensis* (Ludlow, 1904): Structures of the male terminalia.

of the Philippine Islands, in recognition of the valuable contribution he has made and is making to the study of the Culicidae.

LITERATURE CITED

BAISAS, F. E. *Notes on Philippine mosquitoes. I. The* Armigeres *group*. Philippine Journ. Sci. **56**: 485–497. 1935.

BARRAUD, P. J. *Family Culicidae. Tribes Megarhinini and Culicini*. Fauna of British India, including Ceylon and Burma: Diptera **5**, 463 pp. London, 1934.

BOHART, R. M. *A synopsis of the Philippine mosquitoes*. U. S. Nav. Med. 580, 88 pp. Washington, 1945.

THURMAN, ERNESTINE B. *Revalidation of three species of* Armigeres *Theobald, 1901 (Diptera: Culicidae)*. Journ. Washington Acad. Sci. **48**: 186. 1958.

HIGH-TEMPERATURE TRANSFORMATIONS

In the high-temperature research program of the National Bureau of Standards, attention is given not only to measurement of properties of materials at elevated temperatures, but also to the way in which materials are transformed and their properties change as the temperature rises. Interest centers on the rates at which various properties change, temperature ranges in which special phenomena occur, sudden transitions that take place at fixed temperatures, and changes induced by combining high temperature with high pressure. The usefulness of a material for high-temperature applications is largely determined by the nature and extent of such changes.

As a solid is heated it expands, and the expansion may continue smoothly up to the melting point. However, for certain solids the volume may change abruptly at some fixed temperature even well below the melting point; this signals a major structural change, called an *inversion*, caused by rearrangement of the atoms into a different crystal pattern. As heating continues, the atomic arrangement may change to allow a certain amount of freedom in the interatomic bonding, so that the solid begins to flow or creep, with important consequences for the engineering properties of the material.

At a definite temperature transformation from solid to liquid occurs—that is, the solid melts. Interest then shifts to such properties as viscosity and surface tension and their rates of change with temperature. In some cases, if the temperature of the liquid is suddenly and substantially reduced, the material solidifies in the noncrystalline, vitreous state. The constitution of such quenched or frozen liquid-glass is a subject of special study.

The transition from solid or liquid to gas is another change of prime importance at high temperatures; the rates at which such changes occur determine the stability of the material to erosion and evaporation. The effects of other gases in the environment, which often have considerable influence on the evaporation process, must also be studied.

Superimposed on all the transformations mentioned are the effects of impurities, whether present in large or only trace amounts.

Finally, the role of an increase in pressure must be considered. Its effect on the properties of solids is usually opposite to that of an increase in temperature. Study of the interplay of these 2 factors has proved one of the more interesting areas of modern high-temperature physics and chemistry.

Research at the Bureau is concerned with each of these various changes in the behavior of materials as they are heated. In the following brief descriptions are given of work being done on some of them.

INVERSION

Inversion studies are of interest because they contribute to our knowledge of the volume stability of materials in various temperature ranges. At the Bureau such studies have been made on refractory oxides, including the technologically important substance, silicon dioxide. This compound has several forms, including quartz and cristobalite. Quartz is a low-temperature form, while cristobalite can exist in 2 modifications that are stable at low and high temperatures respectively. The temperature at which inversion from high- to low-temperature cristobalite occurs has been reported at different values from 180°C to 270°C. In the past this variation has been attributed to heat treatment—the higher the temperature of preparation, the higher the inversion temperature.

This inversion has been reinvestigated by the Bureau, using specially purified material. The results show that inversion occurs at a fixed temperature (271°C) provided that the cristobalite has been prepared at a sufficiently high temperature (above 1,400°C) to effect proper crystal perfection.[1]

Several other refractory oxides that show solid-phase inversion have also been studied. One of the more interesting is zirconium oxide. At low temperatures the crystallographic form of zirconium oxide is monoclinic, but above 1,000°C it inverts to a tetragonal form which is stable up to the melting point. However, the addition of a small amount of calcium oxide to the zirconium oxide stabilizes another (cubic) form; this form persists from melting point down to room temperature without inversion, and therefore without the undesirable volume change that accompanies inversion. Zirconium oxide is thus converted to a useful, volume-stable refractory.

[1] *The inversion temperature of cristobalite*, by R. F. Walker, S. Zerfoss, S. F. Holley, and L. J. Marston, Journ. Amer. Ceram. Soc. (in press).

CREEP AND CRYSTAL DEFECTS

Plastic deformation (creep) and ultimate strength are among the physical properties of solids that depend strongly on the presence of lattice defects and impurities. The Bureau is investigating such processes in metallic oxides; and among these, aluminum oxide was chosen for concentrated study because it is one of the strongest of the refractory materials and is available both as large single crystals and in polycrystalline form.

It was found[2] that single-crystal aluminum oxide begins to exhibit creep at 900°C; at 1000°C some of the crystals could be stretched by 2 percent. This extension always results from the same type of motion relative to the crystal structure—that is, by slip along the hexagonal base plane in the direction of an "a" axis; so that plasticity at 1000°C is an extremely anisotropic property. For extension to occur, the tensile stress must be applied obliquely to the base plane; if the stress is either parallel or perpendicular to the base plane no creep appears until the temperature is increased to 1600°C, when some other, unidentified, mode of deformation becomes active. However, at 1500°C a crystal subject to a tensile stress at 45° to the hexagonal base plane can be extended to more then twice its original length.

The deformation occurring in these crystals has two characteristic features. First, it requires an incubation period at 1000°C for as long as 70 hours under stress before measurable creep occurs. If the specimen is then held at the same temperature and under constant stress, there is first a period of increasing creep rate after which the rate decreases, approaching a constant value. At higher temperatures the incubation period is shorter or absent altogether, and a final period of accelerated creep (associated with "necking" of the crystal) may occur.

Secondly, at a given temperature, a certain value of stress—the creep yield stress—must be exceeded to initiate measurable creep; this value of the stress is strongly temperature dependent. At 1400°C a tensile stress of 250 kg/cm² is sufficient to initiate creep; at 900°C, 1560 kg/cm² is required; and at lower temperatures the specimens always failed in a brittle manner without measurable plastic deformation. Further experiments showed that once creep had started at 1000°C, it would continue at a stress considerably below the creep yield stress.

The presence of impurities can raise the stress required to start creep; at 1200°C specimens with less than 1 percent chromium oxide had a creep yield stress about twice as large as that for pure aluminum oxide. These results call for interpretation in terms of the stress necessary to move dislocations in the aluminum oxide structure.

Polycrystalline aluminum oxide[3] behaved in a completely brittle manner at room temperature. However, at 1000°C it exhibited a type of plastic deformation quite different from that found in single crystals. Small amounts of creep took place at stresses well below the creep yield stress for single crystals; the creep began immediately on application of load and the creep rate steadily decreased thereafter. When the load was removed after 10 hours, as much as half the total deformation was recovered by creep in the opposite direction in the following 10 hours. The mechanism of this creep and subsequent recovery is thought to be grain boundary slip.

Creep in aluminum oxide and in other refractory metal oxides which have been studied in less detail depends on two types of defects—dislocations and grain boundaries—and on their interaction with impurities. Dynamic measurement of elastic moduli and internal friction provide a sensitive means for studying defects and impurities; a method has been developed for making such measurements at temperatures above 1000°C. Experiments are now under way to study the effects of grain boundary viscosity and dislocation motion on the temperature, frequency, and time-dependence of Young's modulus and the internal friction.

VAPORIZATION AND SUBLIMATION

Advanced research on rockets and nuclear power plants has emphasized the inadequacy of present knowledge regarding vaporization or sublimation processes at high temperatures. The lack of knowledge results in part from the view—held not too long ago—that the vapor phase plays no important role in the high-temperature processing or technological application of solids. However, a growing body of evidence suggests

[2] *Plastic deformation of ceramic-oxide single crystals II*, by J. B. WACHTMAN, JR., and L. H. MAXWELL, Journ. Amer. Ceram. Soc. **40**: 377. 1957.

[3] *Creep of crystalline nonmetals*, by J. B. WACHTMAN, JR., *in* "Creep and Recovery." American Society for Metals, 1957.

that while sublimation processes may not in general be rate-determining, they often have a major influence on reactions at high temperatures.

In line with the changed outlook, it is no longer common to assume that metals vaporize as monomers, or that ionic compounds retain in the vapor phase the valency relations characteristic of the solid phase. High-temperature chemical studies have in many cases revealed a complete reversal of low-temperature behavior; so that the experimenter is faced with the possible existence of a large number of molecular species quite beyond his usual experience.

Four main aspects of high-temperature vapor phenomena are of current interest. These may be termed the kinetic, microscopic, thermodynamic, and chemical aspects, and are concerned, respectively, with: (1) the quantity of material that vaporizes from unit area in unit time, or the rate of linear regression of a surface in a vacuum or in contact with various gases; (2) the mechanism by which individual atoms or ions acquire sufficient energy to leave the surface; (3) the energies associated with phase changes and reaction; and (4) identification of the vaporizing species and the reactions occurring at the interface between solid or liquid and gas phases.

These aspects are not entirely independent. Thus, if kinetic data on loss of weight in a vacuum is combined with data on molecular weights of the vaporizing species, one can calculate the equilibrium vapor pressure and the heat of vaporization. Or, knowing the elements involved and the order of magnitude of the thermodynamic functions, a reasonable estimate can be made of the vaporizing species present.

Recently the Bureau has been measuring the loss in weight at high temperature of single and polycrystalline specimens of known surface area. Changes in weight are measured with a Gulbransen-type microbalance designed for loads up to 4 grams and with a sensitivity of 1 microgram. Specimens are suspended from the balance and, if they are electrically conducting, are heated by direct induction. If nonconducting, they are suspended in an inductively heated furnace; i.e., the specimen is held near a "susceptor", or material capable of being heated inductively. Choice of material and design for the susceptor present severe problems, since the susceptor can interfere with the free escape of molecules from the specimen and can also react harmfully with both the specimen and surrounding gases.

This problem is also being approached with the help of a solar furnace, and various other measuring techniques are being used. Both the Knudsen technique and transpiration methods find application in the problems under study, and it is planned eventually to use mass-spectrometric methods to establish the molecular weights of the vaporizing species. Studies are now being made of the different measurement techniques to determine the relative merits of each.

As an example of the results obtained thus far, it has been possible to show that water vapor has no measurable effect on the rate of evaporation of alumina up to 1600°C, but that at the melting point (2050°C) it considerably enhances the rate of evaporation. Furthermore, by increasing the partial pressure of oxygen in the surrounding region, the rate of evaporation can be retarded.

HIGH TEMPERATURE PLUS HIGH PRESSURE

It is well known that greater pressure favors the formation of compounds with higher density; so that, for example, the pressures existing far below the earth's surface are largely responsible for the formation of gems and other high-density substances with unusual properties. An investigation now under way aims to imitate this natural process and, by a simultaneous application of high temperature and high pressure, to synthesize crystals of high purity and to measure precisely their properties.

Thus a form of talc has been produced in which part of the water is replaced by fluorine; this new form has proved stable, that is, it persists after the pressure and temperature are returned to normal. Similar experiments with water and with lime, on the other hand, generated crystalline forms that continued only as long as the extreme conditions were maintained. Also, the plastic, polytetrafluoroethylene, was found to take several new but temporary forms. In another experiment, the gem, beryl ($3BeO \cdot Al_2O_3 \cdot 6SiO_2$) was synthesized and its stability limits, as well as those of natural beryl, were determined.

An unusual piece of apparatus used in this work is a 7.5-carat diamond confiscated from a smuggler by the Bureau of Customs and turned over to the National Bureau of Standards by the General Services Administration. The diamond is a flawless specimen of the rare type II that is transparent to infrared radiation up to wavelengths of 20 microns. This has the advantage

that, when the diamond is used as a pressure cell, it is possible to obtain the infrared transmission spectrum of the material being studied; and this, in turn, yields important information about changes taking place in the arrangement of the atoms within the material.

The original emerald-cut diamond was modified into a pressure cell by drilling a hole 0.015 in. in diameter through its center. Two pistons of hard tool steel that closely fit the hole are inserted, one from each end, with the sample under study between them. Because of the small cross-section of the cell, a force of only 80 lb is required to bring the internal pressure to 450,000 psi (the maximum that can be attained without danger of splitting the diamond).

Among the other equipment for such studies are steel bombs fitted with opposing pistons of special alloys. External force is applied by hydraulic press and internal pressures as high as 1 million psi and temperatures up to 1500°C are obtained. Alterations of the specimens within the pressure chambers are followed by measuring the changes in volume and electrical properties; in some experiments more indirect methods must be used.

STUDIES OF ELECTROLESS PLATING

Increased understanding of the conditions favoring "electroless plating" has resulted from recent research at the National Bureau of Standards. This chemical deposition process[1] for plating nickel and cobalt on metal surfaces, was developed a decade ago by the Bureau. It is similar in many respects to electroplating but does not employ an electric current. Although adapted by a number of industries for specific applications, electroless plating has not been systematically studied to any great extent. Thus, to obtain further information on the nature of the deposition, C. de Minjer[2] and A. Brenner of the Bureau's electrodeposition laboratory have been investigating the variables that effect the rate of nickel plating and the degree of protection that the coating provides.[3]

Unlike electrodeposition, electroless plating can be used to build up smooth, uniform coatings to a definite thickness over irregularly shaped objects without producing nodular deposits on edges and corners. In other chemical processes for metallic films, the depositing metal is randomly distributed over the container walls as well as over the objects immersed in the solution. Also, after several minutes, the reaction runs to an end and the exhausted solution must be discarded. With the electroless process, however, a nickel coating is deposited only on certain catalytic metals, such as iron, nickel, cobalt, and palladium; deposition does not occur elsewhere in the bath. Furthermore, by periodically replenishing the bath with the appropriate chemicals, the system can be run continuously for hours or even days. Since the reaction is autocatalytic, that is the nickel itself catalyzes the process, the deposition continues once a nickel surface is obtained on any object. Non-catalytic metals can be made catalytic by immersion in a dilute solution of palladium chloride, which coats the metal surface with an almost invisible film of catalytic palladium.

Electroless nickel deposits are not pure nickel but consist of a nickel-phosphorus alloy containing about 8 percent phosphorus. The deposits are bright and much harder than pure nickel deposits.

The electroless process involves the reduction of hot nickel salt solutions, such as the chloride or sulfate, with pure sodium hypophosphite. An organic acid, such as glycolic or citric acid, is added to the bath as a combined buffering and complexing agent. Actually the reaction utilizes only about one-third of the hypophosphite reducing power because a concurrent reaction between the hypophosphite and water produces hydrogen and phosphite.

Experiments were conducted on the rate of deposition at various values of pH. The originally developed electroless bath deposited coatings at the rate of only a few tenths of a mil per hour and rates of the order of 1 mil per hour were desirable. Although the acidity increases during operation of the bath, it was not feasible to control the pH during the plating. Instead, a relatively large volume of the bath (1 liter), was used

[1] *Electroless plating on metals by chemical reduction*, NBS Tech. News Bull. **31:** 111, 1957.

[2] Present address: Philips Research Laboratory, Kanstanje Laan, Eindhoven, Holland.

[3] For further technical information, see *Studies on electroless nickel plating*, C. DE MINJER and A. BRENNER, Plating **44:** 1297. 1957.

to plate a relatively small specimen (having an area of only 12 cm²). Under these conditions, the change in hydrogen ion concentration was not significant.

An increase in the acidity of the bath considerably reduced the rate of plating. For example, a decrease in the pH of the bath from 5 to 4 halved the rate. Ordinarily a higher pH could be maintained by continually adding alkali but the upper value of the pH is limited by the precipitation of nickel phosphite. This reaction is undesirable because the presence of a precipitate leads to spontaneous decomposition of the bath. Thus, the optimum pH of the electroless bath is limited at the lower level by the decrease in the rate of nickel deposition and at the higher level by the diminishing solubility of nickel phosphite. The most satisfactory pH for the acid bath was found to be between 4 and 4.5.

The organic acids used for the buffering and complexing in the baths were found to have specific effects on the rate of deposition. Hydroxyacetic (glycolic) acid yielded a higher rate of deposition than most of the other acids, with the exception of lactic acid. However, the lactic acid bath was not as stable and produced rougher deposits. The rate of deposition reached a maximum at a specific concentration for each acid. Since the acids do not change the chemistry of the reaction, they may influence the rate through adsorption on the active nickel surface. Thus, the maximum in the rate curve can be explained on the basis that a low adsorption of the acid accelerates the reaction while a high adsorption poisons the catalytic surface.

Several hypotheses have been suggested to explain the electroless plating mechanism. The suggested theory involves a two-step process. In the first step, hypophosphite is catalytically decomposed to release hydrogen. In the second step, energy liberated in the discharge of hydrogen is transferred to the nickel ion, and activates the latter so that it can react with the hypophosphite ion. The nature and rate of hydrogen release determine the rate and efficiency of the nickel deposition. The hydrogen overvoltage on a metal surface may be taken as a measure of the ease of hydrogen liberation on the surface. A low overvoltage should facilitate the discharge; however, the energy for activating the nickel ion would also be low. The hydrogen should possess more energy for activation, if released from a high-overvoltage surface but its discharge would occur less readily. Consequently, some intermediate overvoltage should be the optimum for the deposition of nickel.

The suggestion that there should be a correlation between overvoltage and rate of plating led to a study of the influence of certain reagents on electroless plating. Although the correlation between overvoltage and the plating rate was not actually established, it was found that small concentrations of certain addition agents appreciably increased the rate, slightly higher concentrations decreased the rate while still higher concentrations prevented deposition. Certain substances, classified as catalytic poisons, in concentrations of about one part per million of solution markedly raised the rate of deposition. As with organic acids, the effect of these substances reached a maximum at a certain concentration. Thiourea and potassium thiocyanate gave the most significant effect. The former greatly increased the rate of deposition, producing a noticeable effect even in a concentration as small as 0.1 mg/l. As yet, it has not been determined whether these additives can be used in practical plating operations.

Outdoor exposure tests were made of plated steels to compare the protective value of electroless nickel deposits with that of electrodeposited nickel and nickel-phosphorus alloys. Samples were prepared from both acid and alkaline types of electroless baths. Results showed that electroless nickel coatings—from acid baths—offered steel greater protection against rusting than did electrodeposited coatings. Although somewhat tarnished, the electroless plates had only a few rust spots at the end of a 15-month period, while the electrodeposited nickel of the same thickness and under the same conditions rusted considerably. The protective value of the electroless nickel deposits was equivalent to that of the electrodeposited phosphorus alloys which contained about 9 percent phosphorus.

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